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Stratospheric Intrusions Over Northern California During CABOTS: A Study of Ozone Transport and the Influence on Surface Ozone Pollution in the Sacramento Valley

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STRATOSPHERIC INTRUSIONS OVER NORTHERN CALIFORNIA DURING CABOTS: A STUDY OF OZONE TRANSPORT AND THE INFLUENCE ON SURFACE OZONE POLLUTION IN THE SACRAMENTO VALLEY

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ABSTRACT

STRATOSPHERIC INTRUSIONS OVER NORTHERN CALIFORNIA DURING CABOTS: A STUDY OF OZONE TRANSPORT AND THE INFLUENCE ON SURFACE OZONE POLLUTION IN THE SACRAMENTO VALLEY

By Jodie Clark

Stratospheric intrusions occur above California throughout all seasons. Stratospheric intrusions are known to transport ozone rich stratospheric air into the lower troposphere, influencing surface ozone, especially in the mountainous regions of the western US. These intrusions potentially influence the surface ozone concentrations to be above the health-based national ambient air quality standard. Potential Vorticity is a widely accepted tracer of stratospheric air masses being injected into the troposphere. Stratospheric intrusions during the last few weeks of the California Baseline Ozone Transport Study are identified over Northern California, influencing air masses above Bodega Bay and Sacramento. Utilizing daily ozonesonde data from Bodega Bay CA, a downward progression of increasing ozone from the point of stratospheric air injection to the surface is tracked. Analysis of surface ozone from the Bodega Bay surface ozone monitoring station resembles this. A comparison of surface ozone observations in Bodega Bay and 14 surface sites in Sacramento leads to a better understanding of regional surface ozone variations. The surface ozone data observed at the higher elevation surface sites were correlated with elevated ozone captured by the ozonesondes at similar levels. Stronger correlations are found between higher elevation surface ozone and the elevated ozonesonde data, an indication of regional similarities.

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LIST OF ABBREVIATIONS

BAAQMD	Bay Area Air Quality Management District
BBY	Bodega Bay
CABOTS	California Baseline Ozone Transport Study
CARB	California Air Resources Board
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño-Southern Oscillation
EPA	U.S. Environmental Protection Agency
GFS	Global Forecast System
MDA8	Maximum Daily 8-hour Average
MERRA-2	Modern-Era Retrospective analysis for Research and Applications version 2
NAAQS	National Ambient Air Quality Standard
NASA	National Aeronautics and Space Administration
NSV	Northern Sacramento Valley
NOAA	National Oceanic and Atmospheric Administration
PacNW	Pacific North West
PV	Potential Vorticity
QBO	Quasi-Biennial Oscillation
SAC	Sacramento Valley
RH	Relative Humidity
SH	Specific Humidity
SJSU	San Jose State University
SJV	San Joaquin Valley
TOPAZ	Tunable Optical Profiler for Aerosol and oZone

Introduction

Ozone as a Surface Pollutant and EPA Standards

Ozone in the troposphere is a regulated air pollutant which can deteriorate the health of humans and ecosystems (Oltmans at al., 2008). It is accepted that surface ozone concentrations are comprised of background ozone, regional ozone, and local ozone influences (Parrish et al. 2010). The background ozone would be that measured at the coast which is transported inland. Regional ozone is then defined as ozone contributions that are relatively homogenous for a considered region, and local ozone contributions come from only very local influences. To remove as much transient local influence on observed ozone concentrations as possible, the maximum daily 8-hour average ozone is often the value of importance. These are some of the considered values of ozone when examining the U.S. Environmental Protection Agency (EPA) set National Ambient Air Quality Standard (NAAQS).

It is understood that the EPA acknowledges that if the ground-based surface level ozone reaches a level in exceedance of the NAAQS due to stratospheric influence, the air quality monitoring data may be excluded from regulatory determinations (Lin et al. 2012). Acknowledged from Langford et al. (2009), through the Clean Air Act, the EPA sets the NAAQS for surface-level ozone and other pollutants that are deemed as a threat to public health and welfare. The surface pollution standards mark the boundary between the background values of a pollutant and concentrations above which become detrimental. Exposure to greater concentrations becomes harmful to public health or welfare (Parrish et al. 2010).

Background Ozone

The policy relevant background values for surface-based ozone are those which would exist in the absence of anthropogenic emissions across the North American Continent. Background ozone would be comprised of ozone formed by photochemical reactions connected to volatile organic compounds, carbon monoxide, and nitrogen oxides from biogenic sources, wildfires and lightning, and includes ozone transported ashore from the Pacific and ozone transported from the stratosphere to the troposphere air. Yet it has been challenging to identify and quantify the influence of stratospheric ozone into the troposphere (Langford 2009, Lin et al. 2015).

From Bourqui and Trépanier (2010), some of the non-conservative processes at the tropopause which will transport stratospheric air to the troposphere include the turbulence caused by strong wind shear associated with tropopause folds, the breaking of gravity waves, and the radiative cooling identified with anticyclones. Since the photochemical lifetime of ozone is about 22 days in the free-troposphere, and these non-conservative processes are on the order of a few days, stratospheric ozone can significantly influence the background ozone concentration, and potentially pollution at the surface.

Oltmans et al. (2008) separated out the data of onshore flow at Trinidad Head, CA and used these data to examine the background ozone at the surface. Seasonal and diurnal patterns are found among surface ozone data at Trinidad Head, CA. Seasonally, ozone concentrations were shown to peak in April, decrease sharply to a minimum in July, and then steadily increase to the peak once again.

In a similar manner, Oltmans et al. (2008) also examined 10 years of Trinidad Head ozonesonde data for onshore flow. The observed air entering from the Pacific in the lower troposphere (1 – 5 km) above the marine boundary layer provides a good picture of the background ozone content. The onshore air flow in the lower troposphere over northern California is likely to progress inland over the North American continent. Seasonal ozone variations in the lower troposphere are minimum in winter, and peak in spring and remain amplified throughout the summer (April – September). During all months, at 2 km, the concentration was on average 50 ppb or greater. Therefore, plenty of ozone resides above Trinidad Head with potential to mix down to the surface.

Stratospheric Intrusions

It is known that stratospheric intrusions typically develop in the high and mid-latitudes. The question of how much influence stratospheric ozone has on tropospheric ozone is still under debate (Hsu and Prather, 2009; Lin et al., 2012). There has been debate among atmospheric scientists about what extent stratospheric ozone intrudes into the troposphere to influence the surface pollution levels above the health-based limit (Ding and Wang, 2006; Langford et al., 2009; Lin et al., 2012).

Already known today, the dry airstream of a midlatitude cyclone allows for the descent of stratospheric ozone to the mid- and lower troposphere (Cooper et al., 2001; Stohl et al., 2003; Lin et al., 2012). It is known that deep stratospheric intrusions transport ozone-rich stratospheric air to the lower troposphere, intermittently enhancing ozone concentrations in the lower troposphere. The deep descent of stratospheric air has been defined as that which crosses the dynamical tropopause and travels to 700 hPa pressure level within 5 days (Bourqui and Trépanier, 2010).

It is known that stratospheric ozone transports to the middle and the lower troposphere primarily through the dry airstream of a mid-latitude cyclone (Lin et al. 2015). The varying placement of storm tracks across the North Pacific in winter is associated with the El Niño-Southern Oscillation (ENSO) cycle. During El Niño, the path is more southerly and influences the southern US and even the Gulf of Mexico (Langford et al., 1998). In La Niña, the storms follow a northerly path as high pressure over the Pacific causes the polar jet stream to meander, bringing storms to the Pacific Northwest. These cold front passages aid in deep tropopause folds through which stratospheric ozone can be transported to the lower troposphere.

From Bourqui and Trépanier (2010), it is noted that for the clusters of stratospheric air to reach the lower altitudes of the troposphere, the air must slide down along sloping isentropes. The known causes of the descending isentropes are either a low potential temperature anomaly associated with the positive potential vorticity (PV) anomaly, and/or a cross-baroclinic motion towards a warmer area (Bourqui and Trépanier, 2010).

PV Values and Uses

For decades now, among a handful of other ways, stratospheric intrusions have been identified through the meteorological tracer PV and layered structures in ozone profiles (Danielson et al., 1987; Oltmans et al., 1996; Roelofs et al., 2003; Lin et al., 2012). When defining the tropopause, it is well established already that the rise in ozone corresponds well with the strong rise in PV, starting as low as 1 PVU, and possibly lower

(Trickl et al. 2014). Values ranging from 1-5 PVU are the most commonly accepted values, with the lower values capturing the tropopause folds to a greater depth than the higher.

The implemented study of Škerlak et al. (2014) defined the height of the tropopause by the classical dynamical tropopause, 2 PVU/380 K, as it is superior in all aspects and situations. PV is conserved in adiabatic frictionless flow, so an air parcel can only cross the PV-defined tropopause if PV is changed through diabatic or other non-conservative processes. The PV tropopause captures the complexity and 3-D structure of the tropopause that is recognized near jet streams, cut-off lows and cyclones. Therefore, a stratospheric intrusion can easily be defined by abnormally high PV values in the troposphere (Škerlak et al. 2014).

Stratospheric Ozone Transport

Case study 1

Škerlak et al. (2014) performed a 33-year global climatological study of stratosphere-troposphere exchange. This study utilized reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) for the period of 1979 – 2011. This study found that the west coast of North America is one of the hotspots for not only stratospheric intrusions, but deep stratospheric intrusions that will cross the 700 hPa level or 3 km level, allowing for mixing into the boundary layer. Similar to that previously noted by Wernli and Bourqui (2002).

In regions where the mass flux across the tropopause is greater, so is the mass flux of air across the 700 hPa level. Of the 33-year global climatological study by Škerlak et al.

(2014), 10% of the mass fluxes cross the 700 hPa pressure level and 5% cross the 800 hPa pressure level. Both of which occur over the California region in all seasons of the year, often following North Pacific storm tracks. The mass flux of stratospheric air crossing the tropopause above California is found to be weakest in the summer, and strongest in spring. Springtime is also associated with the most occurrences of deep stratospheric intrusions.

The study performed by Škerlak et al. (2014) found seasonal differences in the ozone concentrations at the tropopause. Within the region above the state of California during the spring and summer, concentrations of ozone near 120 – 130 ppb are expected. Smaller ozone concentrations were found during the autumn and winter seasons, values of 80 – 90 ppb expected.

Škerlak et al. (2014) found seasonal characteristics in ozone fluxes across the tropopause defined in the region above the state of California. The average ozone fluxes across the tropopause in spring are near 150 kg/km^2 a month. In the summer months, average ozone fluxes across the tropopause are near 100 kg/km^2 a month. During both seasons, the higher fluxes are over northern California as compared to southern California. But the models also show that the downward sloping isentropes descend much closer to the surface over southern California and Baja.

Ozone fluxes across the tropopause are found to reach the planetary boundary layer in each season across California (Škerlak et al. 2014). Average values of ozone fluxes into the planetary boundary layer associated with deep stratospheric intrusions are found to decrease from spring to summer. Fluxes in spring range from about 5 – 50 kg/km^2 a month. The summer months range from about 0 – 30 kg/km^2 a month. During both seasons, the flux is weaker at the coast and lower elevations and stronger inland at the higher elevations.

Case study 2

Bourqui and Trépanier (2010) investigated the dynamics of the descent of a stratospheric air mass into the lower troposphere. The goal of this study was to gain insight into the meteorological conditions which are necessary for stratospheric intrusion events to occur and to what extent is the stratospheric air mass diluted by tropospheric air influences. The study focuses on data captured at twenty-three sites across North America in August 2006 from the INTEX-B Ozone Network Study (IONS) campaign. During this period, half of the sites were able to perform daily ozonesonde launches. Four vertical profiles indicated deep stratospheric intrusions with high ozone concentrations and very low relative humidity (RH) observations within the lower troposphere.

Each vertical profile was further investigated, including a profile from Trinidad Head, CA of interest on August 16. The use of the LAGRangian ANalysis Tool (LAGRANTO) created cluster trajectories for the analysis of deep intrusion cases. Bourqui and Trépanier (2010) found that typically a trajectory would take 1 – 2 days to cross the tropopause, defined at 2 PVU, and another 3 days to cross the 700 hPa surface. Each cluster remained compact until reaching the lower tropopause where the trajectories dispersed at different rates. The specific humidity (SH) along the trajectories are low in the stratosphere and gradually increase once in the troposphere. The SH quickly increased coinciding with the dispersal of the trajectories in the lower troposphere, above the planetary boundary layer. The three distinct phases of the intrusion are the transport of stratospheric air across the tropopause, the free descent with minimal tropospheric mixing, and the quasi-horizontal dispersion into the lower troposphere.

Case study 3

A study performed by Trickl at al. (2014) examines the mixing of tropospheric air with the intruded stratospheric air in the German Alps. Since 2007, routine measurements from lidar soundings for ozone, water vapor, and aerosol have been in operation. Trickl et al. (2014) discovered that the layers of intruded stratospheric air were often observed with RH values approaching zero.

According to Trickl et al. (2014), without convective processes or strong wind shear the mixing of tropospheric air into the intruded stratospheric air would be a very slow process. It is suggested that the air mass could remain stratospheric in nature for a period of 1 – 2 weeks. The conservation of the water vapor mixing ratio of the stratospheric air mass as it travels to the Alps confirms that the entrainment of tropospheric air into the intruded stratospheric air mass is low. Trickl et al. (2014) found that in examining multiple cases, during the majority the intruded stratospheric air had water vapor mixing ratios much drier than the typical upper tropospheric values.

Case study 4

A goal of the study performed by Cox et al. (1997) was to see if the UK Universities Global Atmospheric Modelling Programme (UGAMP) General Circulation Model (GCM) was able to capture the outcome of stratospheric air as it injects into the troposphere. This work examined measurements observed during a cut-off low which progressed across the northern Atlantic Ocean during the European Union Transport of Ozone and Stratosphere/Troposphere Exchange (TOASTE) in early October 1990.

The model was initialized with ECMWF data for October 6, and explored the varying height of the tropopause utilizing values for lapse rate, static stability, PV and SH. The height of the tropopause for the associated trough was determined through PV and SH. Cox et al. (1997) examines PV values for the tropopause ranging from 1 – 5 PVU, the range of accepted values. It was concluded that the value of 1 PVU and the SH value of 0.15 g kg^{-1} are best suited in the investigation of deep stratospheric intrusions. That being the case the sub-structures associated with the intrusion, both the folds and the streamers (i.e. the long-lived quasi-horizontal tongues of stratospheric air that curve anticyclonically from the trough) can be identified.

Cox et al. (1997) found that the fold and streamer associated with the trough extended to near 800 hPa (~3 km) with modeled PV and that modeled SH follows a similar structure to just below 4 km.   The initial fold existed across the length of the jet streak, i.e. the local wind speed maximum within the jet stream, and that the fold had a larger exit region than entrance. After a day, the fold began to decay and the formation of a low level ‘tube’ of high PV was noted. A secondary fold occurred as a cut-off low developed. During the 7-day model run, multiple folds were found in the model data associated with other jet streaks near the trough. The streamer associated with the trough extends southwards. Cox et al. (1997) examined the tube-like structure of the streamer on the 310 K isentropic surface which spanned both the stratosphere and the troposphere. A PV height cross-section showed the tube structure in the lower tropopause between 2 – 4 km with a high PV core that originated in the stratosphere. The observed lifetime of the PV streamer for this case study was 5 days. This gives a 6-day period of stratospheric air transport from the stratosphere into the troposphere.

Surface Ozone

It has been suggested by many that background ozone levels are greater than previously assumed within the predominantly mountainous western U.S. Langford et al. (2009), found that during the springtime in the metropolitan area of Denver, CO, stratospheric intrusions brought extremely dry, ozone-rich air to the surface sites that well exceeds the NAAQS. Yet evidence of these intrusions passed after just a few hours. This demonstrates that the commonly performed weekly sampling of tropospheric ozone is not consistent enough to provide adequate data. To capture the full impact of stratospheric intrusions on background and surface ozone conditions, daily measurements would be beneficial.

It is proposed that the climatological increase of surface ozone is partly due to long-range transport of Asian emissions (Oltmans et al, 2008), increasing background ozone. Therefore, if considering increases in surface ozone due to stratospheric intrusion and boundary layer mixing, long-range transported pollutants should be considered in the ozone total. On the contrary, little mixing was found to occur around an intruded stratospheric air mass, especially its core (Trickl et al., 2014).

Bourqui and Trépanier (2010) acknowledge that the high ozone transported from the stratosphere to the lower troposphere would further mix into the boundary layer, contaminating it. Also, that it would be useful for air quality standards to investigate the quantitative relationship between deep stratospheric intrusions and surface ozone concentrations. Deep convective boundary layers typical of the summer and fall could arrest the direct transport to the surface, yet convective mixing [and subsidence (Myrup et al. 1983)] can lead to diluted stratospheric air in the boundary layer. The downward transport of injected stratospheric ozone from the lower troposphere to the surface could be further aided by wave activity, turbulence, or shear created by downslope winds (Langford et al. 2009).

Quantifying the actual amount of stratospheric ozone that contributes to tropospheric ozone is a topic of interest. The layered structures found in vertical ozone profiles measured by ozonesondes is not reproduced well in many global and regional tropospheric chemical transport models (Roelofs et al., 2003; Lin et al., 2012). The models struggle further with deciphering the impacts of stratospheric ozone influence on the surface ozone observations (Lin et al., 2012).

It has been noted by Lin et al. (2012) that stratospheric ozone is more effectively transported to the lower troposphere in the Southwest US. Also, that when the intrusion advects southward after breaking away from the polar jet, the surface air over regions of California, Arizona, and New Mexico are likely to be influenced by stratospheric ozone. Lin et al. (2012) shows that the western US region has greater occurrences of stratospheric intrusions influencing surface ozone concentrations than the eastern US during the spring. In the higher elevations of the western US, the topography intersects the subsiding air easily in comparison to the lower flatlands in the eastern US.

Lin et al. (2012) findings from the GFDL AM3 model run for April – July 2010 were suggestions of strong stratospheric influence in the Sierra Nevada mountain range. The suggestion is made to have more measurements recorded at these rural sites to gain insight into the stratospheric influence on surface ozone in the local urban area.

Case study 1

The study by Lin et al. (2015) performed a 23-year study (1990 – 2012) of modeled mean stratospheric ozone contributions to the surface ozone observations across the US during the months of April and May. It was found that the highest contributions were in the mountainous western United States, with contributions approaching 25 ppbv of stratospheric ozone. This study indicates an influence of stratospheric ozone on the surface ozone concentrations across the state of California ranging from near 15 – 20 ppbv. The greater influence occurred in the more mountainous north west region of the state.

According to Lin et al. (2015), there is a correlation among the amount of stratospheric ozone that enhances western US surface pollution during the months of April and May, and the phase of ENSO cycle. This study shows an enhancement in stratospheric ozone at the surface in a La Niña spring in comparison to a neutral or El Niño spring. Following a La Niña spring, enhancements of surface ozone remain high in association with a greater occurrence of deep stratospheric intrusion events, driving surface ozone values to exceed the NAAQS. It is also suggested that the combination of El Niño with the negative, or easterly phase, of the Quasi-Biennial Oscillations (QBO) would increase the amount of stratospheric air transported to the upper troposphere of the mid-latitudes.

Case study 2

Parrish et al. (2010) found that when studying the correlations between maximum daily 8-hour average ozone observations at urban and rural Northern Sacramento Valley (NSV) sites with the coastal ozone data at and near Trinidad head, the correlations were highly influenced by regional ozone. Correlations weaken as sites of comparison were of different regional origin with topographic separations.

When performing an altitude dependence correlation analysis, Parrish et al. (2010) found that for each of the five NSV sites investigated, each had a significant correlation with average onshore ozone from the 1 – 2.5 km altitude range. These correlations were stronger than the correlations with the coastal surface ozone. Each site correlated best with different sections of this altitude range, seemingly dependent on the altitude of the NSV surface site.

Parrish et al. (2010) found that the strong correlations between the Trinidad Head ozonesondes and the NSV surface sites in the summertime, are weaker in spring and autumn, and were not present in the winter. This shows that the strong summertime surface heating raising the boundary layer heights allows for the vertical mixing of ozone aloft. According to Myrup et al. (1983), a daytime subsidence rate of 5 cm/s is observed over the Sacramento area during the summer at an altitude of 1.5 km.

Objectives

California Baseline Ozone Transport Study (CABOTS)

The California Baseline Ozone Transport Study (CABOTS) occurred in late spring/early summer 2016, May 16 through August 17. The CABOTS project, an air quality study, had four main objectives. The first objective was to gain knowledge into the content and daily variability of ozone vertical profiles as they enter the State from the Pacific. The second objective was to better understand the influence of trans-Pacific long-range transported ozone mixing to the surface sites in the San Joaquin Valley (SJV). Third objective was to gain insight into the spatial and temporal variations in baseline ozone concentrations entering California. The final objective was to gauge and improve the atmospheric resolution global models and those used in the ozone State Implementation Plan modeling.

The collective projects of CABOTS include the National Aeronautics and Space Administration (NASA) Ames Alpha Jet Atmospheric eXperiment (AJAX) flights, the University of California Davis/Scientific Aviation Mooney aircraft measurements, the National Oceanic & Atmospheric Administration (NOAA) Tunable Optical Profiler for Aerosol and oZone (TOPAZ) Lidar at Visalia, and the San Jose State University (SJSU) Ozonesondes in the Bay Area. Figure 1 shows the location of the measurement sites. The NASA team had two flight missions. The missions measured the offshore vertical ozone near BBY, the horizontal ozone aloft between BBY and SJV, and the vertical ozone inland in the SJV. Two secondary, smaller aircraft flights were conducted. These too were to bring insight into ozone values aloft in the SJV. Each of the four flights

Figure 1. Location of SJSU ozonesonde launch site, TOPAZ Lidar profiler, and AJAX Flight waypoint region.

occurred during periods of ozone Lidar deployments. The truck-mounted TOPAZ Lidar at Visalia Airport in SJV measured ground-based ozone profiles up to 6 km for two 3-week periods. The first lidar deploy took measurements in late May and early June during which the AJAX flights took place. The second lidar deploy took measurements in late July and early August during which the Mooney flights occurred. The SJSU team launched near-daily ozonesondes from Bodega Bay, CA during the whole study. A secondary launch site was established in Half Moon Bay, CA for the final few weeks of the study.

SJSU Ozonesondes

It is suggested that weekly ozonesonde measurements at Trinidad Head, CA and Boulder, CO are inadequate to capture the actual variability of mean mid-tropospheric ozone in April – May (Lin et al., 2015). The near-daily ozonesondes launched from Bodega Bay, CA contribute to CABOTS third objective. That is to bring insight to the vertical daily variability of background ozone as it enters the west coast, including those variations due to stratospheric intrusions. As the shallow nocturnal boundary layer heights grow to daytime heights, the higher ozone concentrations aloft begin to mix down in the elevated daytime boundary layer. This, along with the daytime photochemical production of ozone, leads to surface maximum ozone concentrations in the afternoon (Parrish et al., 2010). Therefore, the Bodega Bay ozonesondes were released at 21 UTC (2:00 PM Local Time), in hopes of capturing this maximum.

The phases of ENSO were as follows during CABOTS. The winter of 2015/2016 experienced a very strong El Niño phase. By spring 2016 ENSO became neutral, and it then transitioned to the La Niña phase in the summer 2016. The QBO was in the heart of its westerly (positive) phase during CABOTS, beginning June 2015 lasting through May 2017 (North Georgia Wx, 2018). Therefore, this study occurs when stratospheric air transport is not at its suggested maximum.

Study Objectives

The objective of this study was to gain a better understanding of vertical stratospheric ozone transport during the passage of a stratospheric intrusion event over Northern California. More specifically the objective was to gain knowledge of the daily variability in ozone concentrations that occur at the location of, and below the region of a stratospheric intrusion. The investigation of daily vertical variations of ozone captured by ozonesondes launched at Bodega Bay, CA gives an indication of vertical ozone variations which occur slightly further inland above the Sacramento Valley. Investigation into boundary layer ozone concentrations at Bodega Bay, which are influenced by stratospheric ozone, leads to an increased understanding of stratospheric ozone influences in the southern Sacramento Valley and surface pollution exceedances.

To further investigate the vertical variations in ozone, the stratospheric intrusion was first identified. Intrusions were identified using PV as a tracer of stratospheric air. The upper level jet streaks and cut-off low pressure systems were used as supportive evidence of the intrusion. Daily variations of ozone concentrations measured by Bodega Bay ozonesonde launches before, during, and after the identified stratospheric intrusion events were further analyzed.

If ozone data measured at Bodega Bay were to give an indication of ozone above the Sacramento Valley, the regions needed to be shown as comparable. Modeled regional averages of ozone, PV, relative and specific humidity over Bodega Bay and the Sacramento Valley were compared. Strong time and height similarities were observed between average values over both regions. The intrusions marked by high PV were found concurrently in the upper troposphere above both Bodega Bay and the Sacramento Valley. This gives an indication of the comparability of stratospheric ozone influence in the two defined regions.

An influence of stratospheric ozone was tracked to the Bodega Bay surface from ozonesonde data and observed values were correlated with surface ozone pollution in the Sacramento Valley. The Bodega Bay surface ozone monitoring station recorded increases corresponding with the near surface increases in ozonesonde data. Linear correlations between boundary layer ozone concentrations at Bodega Bay and fourteen surface monitoring ozone stations in the southern Sacramento Valley were investigated. The surface sites were divided into three height categories. Further investigations of height dependency of ozone concentrations were performed for surface monitoring sites of the highest elevations.

The following sections describe the collection of data used in the case study, the methods implemented to analyze the data, the data analysis performed, and concluding remarks including proposed future studies.

Data Collection

Reanalysis

Two sets of reanalysis data were used to show the occurrence of the stratospheric intrusion events during this study. The Global Forecast System (GFS-Analysis) is made up of 31 isobaric levels with a resolution of 1.0° latitude x 1.0° longitude. Data from July 28, 2016 through August 14, 2016 were used to analyze the 250 hPa wind speed and direction over the Pacific Northwest (PacNW), a domain which covers 30.0°N to 60.0°N and 170.0°W to 115.0°W. Within the same PacNW domain, PV data from the Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-2) were analyzed for correspondence. The MERRA-2 model is comprised of 72 hybrid sigma/pressure levels with a resolution of 0.5° latitude x 0.625° longitude. Other supporting variables used from this model include ozone, RH, and SH. The utilized data were within the timeframe of July 25 – Aug 13, 2016.

CABOTS

At Bodega Bay, eighty-six near daily ozonesondes were launched at 2100 UTC (1400 local time) by the SJSU launch team, collecting quality data. Figure 2a, a time/height cross-section curtain plot, shows the 100-meter average ozone concentrations measured during the entire field study. The frequent occurrence of high ozone concentrations in the upper troposphere were clearly recognizable within the data. On a few occasions, relatively high ozone concentrations extend down from the tropopause toward the lower troposphere, impacting below 4 km. For example, on June 11, 2016 a concentration maximum of 145 ppb was observed at 3 km, with concentrations generally greater than 70 ppb in the vertical air column above.

In the lower levels, the observed ozone concentrations would include multiple sources. These sources include ozone mixing upwards from the surface, long-range transport mixing, and mixing from upper level layers due to stratospheric intrusions.

In the lower 2 km, multiple occurrences of ozone concentration pockets greater than 70 ppb were observed throughout the entire study (Fig 2a). Three distinct pockets were visible during the final three weeks of the CABOTS project. On July 27, the observed ozone concentrations approached 120 ppb at 2 km. This very high ozone concentration occurred during the Soberanes Fire in Monterey County (SJSU CABOTS, 2016). Another possible fire influence observed was from August 3 to August 4, during which the Cold Fire in Yolo County was active. During the launch on August 3, the observed concentrations at 1 km reached 100 ppb. The final high ozone concentration pocket

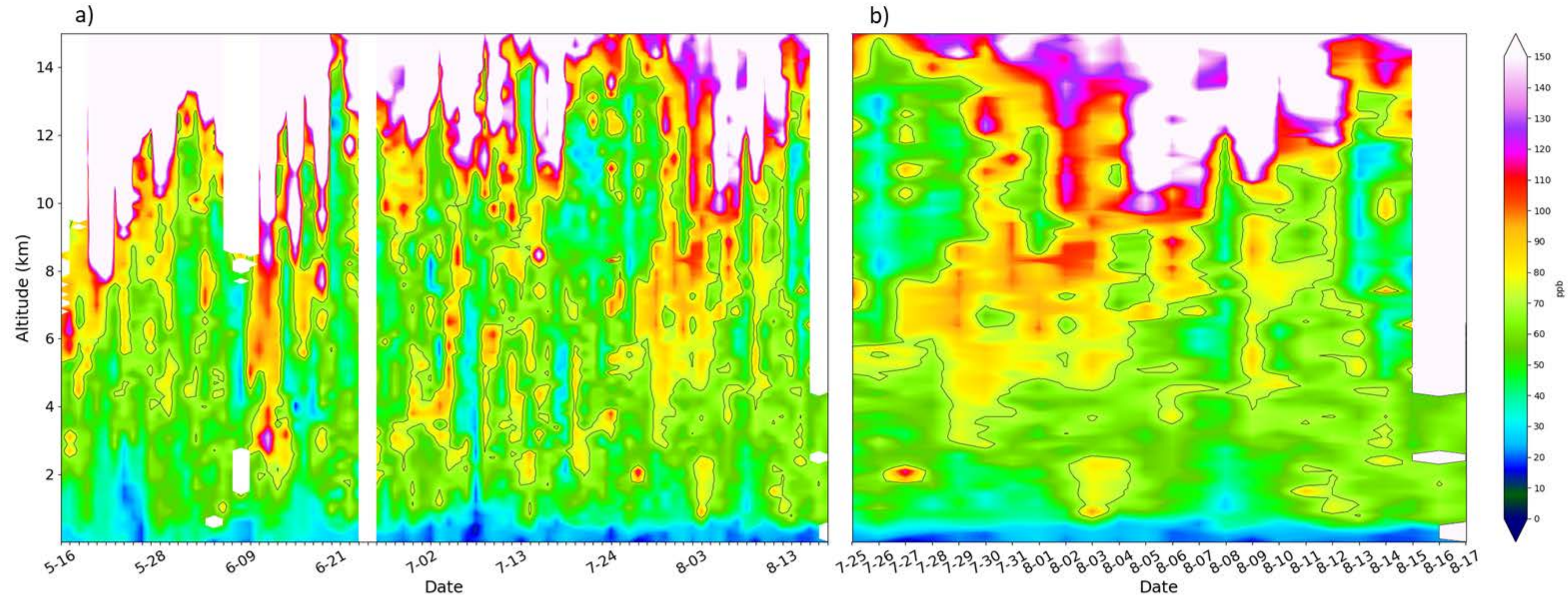

Figure 2. Bodega Bay near-daily ozonesonde observations. Color scale concentrations from 0 – 150 ppb, black line = 70 ppb, the EPA set maximum daily 8-hour average surface ozone standard. a) all CABOTS data, 2016. b) July 25 – August 17, 2016.

captured in the lower 2 km was from August 11 through August 13. A closer observation of these pockets can be seen in Figure 2b. This figure shows the ozone measurements collected during the period from July 25 through August 17, 2016. During this defined case study period, the Air Quality Index for surface ozone pollution in the southern Sacramento Valley was classified as moderate to unhealthy. Analysis of the latter two high ozone occurrences will be discussed further in the Methods and Analysis section, Correlations Among Sites.

Surface Monitoring Stations

Data from fifteen surface ozone monitoring stations were used for analysis of the unhealthy surface ozone conditions in the Sacramento non-attainment zone. Surface ozone data were provided by the California Air Resources Board (CARB). This data set included the hourly average surface ozone values observed during the period of the CABOTS project. Of the many continuous surface monitoring stations across the state, observations from fourteen of the surface sites were used within this case study (Fig 3b). Figure 3a includes the location of the Bodega Bay monitoring site. This gives perspective to the distance inland of the Sacramento surface monitoring stations. The surface ozone data for Bodega Bay were provided by the Bay Area Air Quality Management District (BAAQMD). This data set included surface ozone values observed for every minute, which were averaged to hourly ozone data. The surface station data were analyzed starting on July 25, 2016 through August 17, 2016, the case study period of interest.

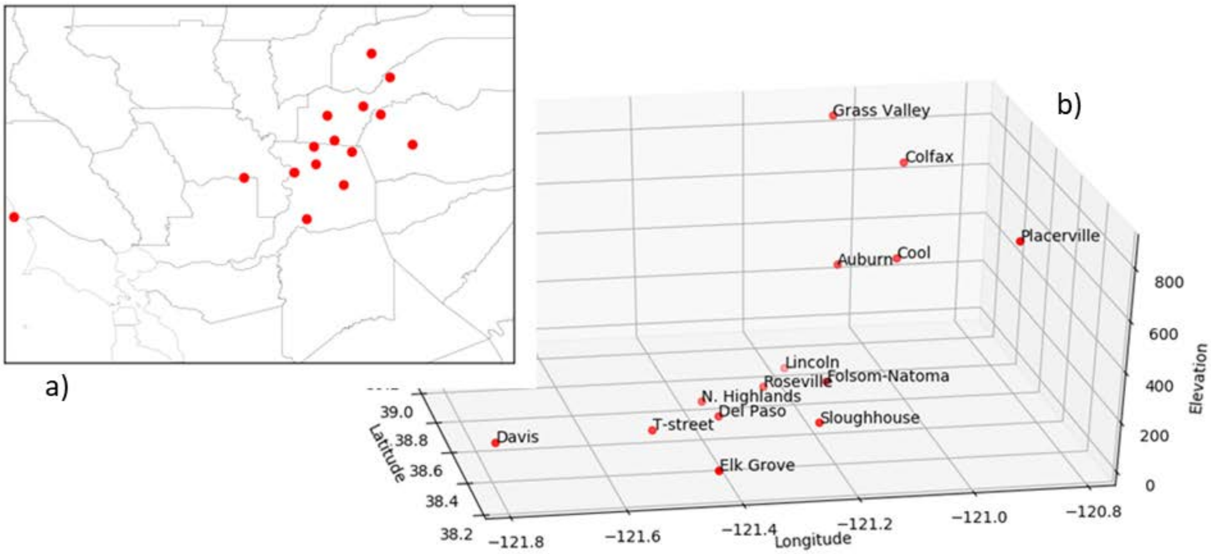

Figure 3. Location of the fifteen surface ozone monitoring stations a) Birds eye view of all surface monitoring sites, with county lines in grey. b) 3D layout of the Sacramento surface stations with location names.

Method and Analysis

Synoptic Overview

To show the occurrence of a stratospheric intrusion, 250 hPa winds for the case study period were analyzed, along with the 11 km MERRA-2 PV, the reanalysis model level closest to the 250 hPa pressure level. These upper-level wind patterns give the placement of the jet stream and jet streaks during the stratospheric intrusion events of interest. Also visible from the upper-wind synoptic patterns over the PacNW were upper level fronts and cut-off lows, both known signatures of tropopause folding (Figs 4, 6, 8). The 11 km MERRA-2 PV analysis marks these same synoptic features (Figs 5, 7, 9). These figures also give an indication of where tropopause heights were either higher or lower over the PacNW domain. The 21z-hour timestamp was chosen for analysis as this hour corresponds with the ozonesonde launches which took place at Bodega Bay. Multiple stratospheric intrusions were noted.

During the case study period, there were three stratospheric intrusion events of interest. Each event has a deeper penetration of stratospheric air into the middle troposphere. In each of the three events, the placement of the jet stream across the PacNW was unique from the others. The dates of occurrence for the intrusion events were as follows: July 27, August 5, and August 9. A value of 1.5 PVU is used as an indication of the tropopause. Values greater than 1.5 PVU are used to indicate stratospheric air, whereas lower values indicate tropospheric air (Figs 5, 7, 9). Therefore, during a stratospheric intrusion event, values of high PV within the troposphere indicate air which is stratospheric in nature, rich in ozone, and exhibiting very low water vapor content. This study also observes a change to high PV near the 8 km level from July 26 through July 27 (Fig 5), near the 5 km level from August 4 through August 5 (Fig 7), and near the 9 km level from August 8 through August 9 (Figs 9). The vertical progression of the intrusion shows the deeper penetration of stratospheric air into the middle troposphere, and the downward progression of travel with time.

The first stratospheric intrusion event occurred beginning on July 27, 2016 into the elevated air above Northern California and remained present into July 28, 2016. The placement of the jet stream across the PacNW was slightly north of center. Starting at the west of the domain, two embedded shortwave lows were pulling the jet stream southward (Fig 4). A weak high-pressure system off the coast of Oregon and Northern California was driving the jet stream towards the north. The main jet streak lies in the northern central half of the domain, with wind speeds approaching 60 m/s.

The top panels of Figure 5 illustrate the MERRA-2 PV values at a height of 11 km. This indicates the association of higher PV values with the previously described jet stream, jet streaks, and low-pressure systems during the first stratospheric intrusion event (Fig 4). The tropopause remains at a higher altitude over most of California. The bottom panels of Figure 5 illustrate the deeper penetration of the stratospheric air mass at a height of 8 km over Northern California. The left panels of Figure 5 represent the MERRA-2 PV values for the date of July 26, 2016 at the 21z afternoon hour. The right panels of Figure 5 represent the MERRA-2 PV values for the date of July 27, 2016 at the 21z afternoon hour. The bottom panels illustrate the stratospheric air mass observed above a narrow strip of Northern California as it progressed up from the south to influence the region by July 27, 2016.

The ultimate importance of this first stratospheric intrusion event was the building of higher pressure over the four corners region of the desert southwest (SJSU CABOTS, 2016). The building of this higher pressure resulted in the northwest transport of moisture in the 3 – 8 km vertical column above Southern California. Along with this came the northwesterly advection of the dry stratospheric air mass over Southern California to influence the air mass above the North Bay Area, the State Capital, and the Tahoe region simultaneously.

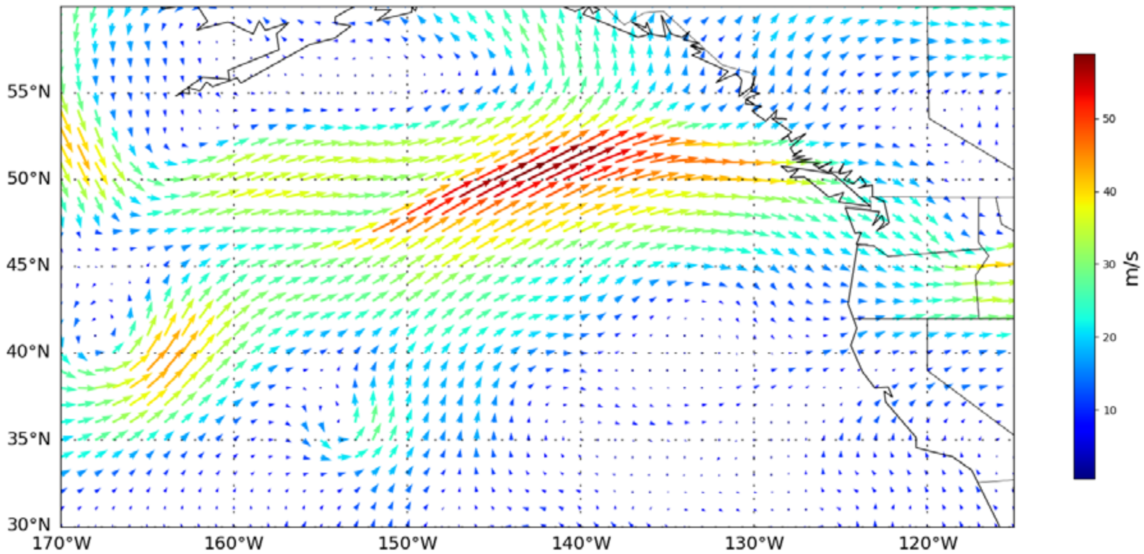

Figure 4. GFS modeled 250 hPa winds over the PacNW domain 07 28 2016 0000z + 0 hr forecast.

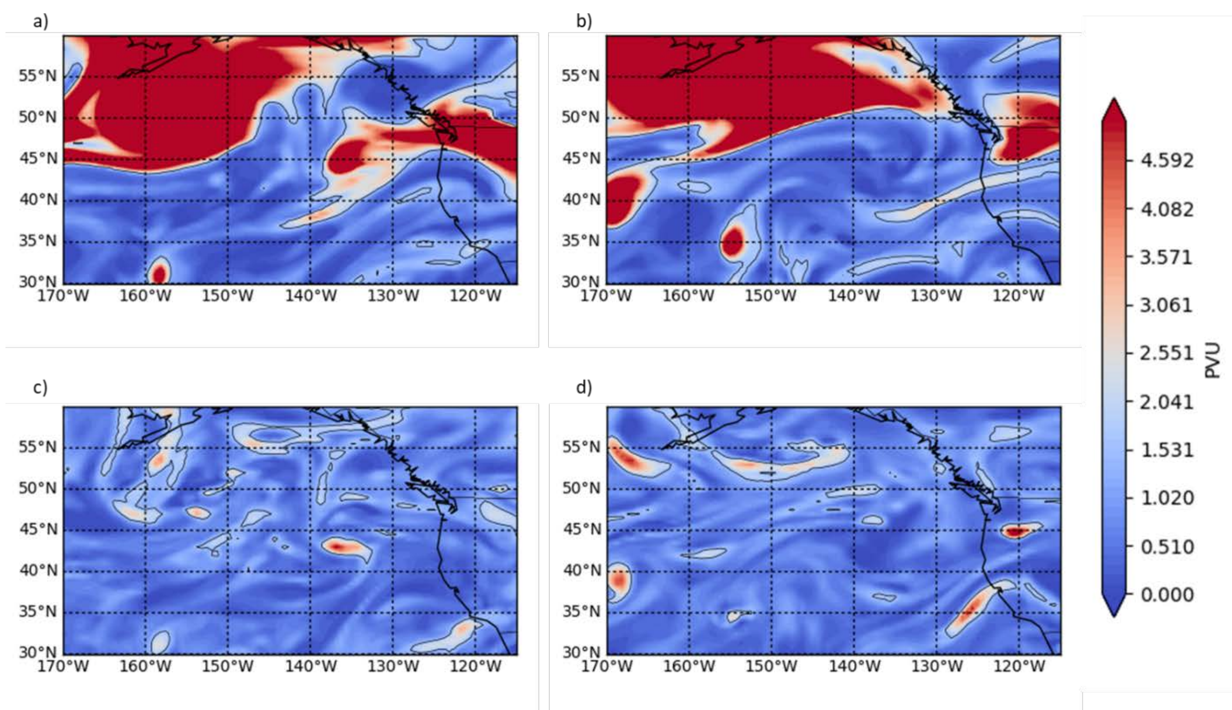

Figure 5. MERRA-2 PV 21z reanalysis data over the PacNW, colors plotted values 0 – 5 PVU, black line = 1.5 PVU a) July 26, 2016 at 11 km b) July 27, 2016 at 11 km c) July 26, 2016 at 8 km d) July 27, 2016 at 8 km.

The second stratospheric intrusion event occurred early on August 5, 2016 above Northern California and remained present through the early hours of August 6, 2016. The placement of the jet stream across the PacNW was low in this event (Fig 6). The wind speeds of the jet stream were weak during this event, with maximum values near 40 m/s. At the northwest corner of the domain, the jet stream diverges southward pulled by a region of low-pressure in the southwest corner of the domain. A high-pressure system in the Gulf of Alaska assisted to keep the placement of the jet stream southward. Also aiding to the jet stream placement were a low-pressure system centered over British Colombia and an embedded shortwave located about 10° off the west coast of Northern California and Oregon. The jet stream traverses across the middle of California in a North Easterly direction, creating low tropopause heights within the region. This included the North Bay Area, the State Capital, and Tahoe.

The top panels of Figure 7 illustrate the MERRA-2 PV values at a height of 11 km. This indicates the association of higher PV values with the previously described jet stream, jet streaks, and low-pressure systems during the second stratospheric intrusion event (Fig 6). The height of the tropopause over Northern California lowered, visible by a wider spread of higher PV values as the jet stream tracks across California. The bottom panels of Figure 7 illustrate the deeper penetration of the stratospheric air mass at a height of 5 km over Northern California. The left panels of Figure 7 represent the MERRA-2 PV values for the date of August 4, 2016 at the 21z afternoon hour. The right panels of Figure 7 represent the MERRA-2 PV values for the date of August 5, 2016 at

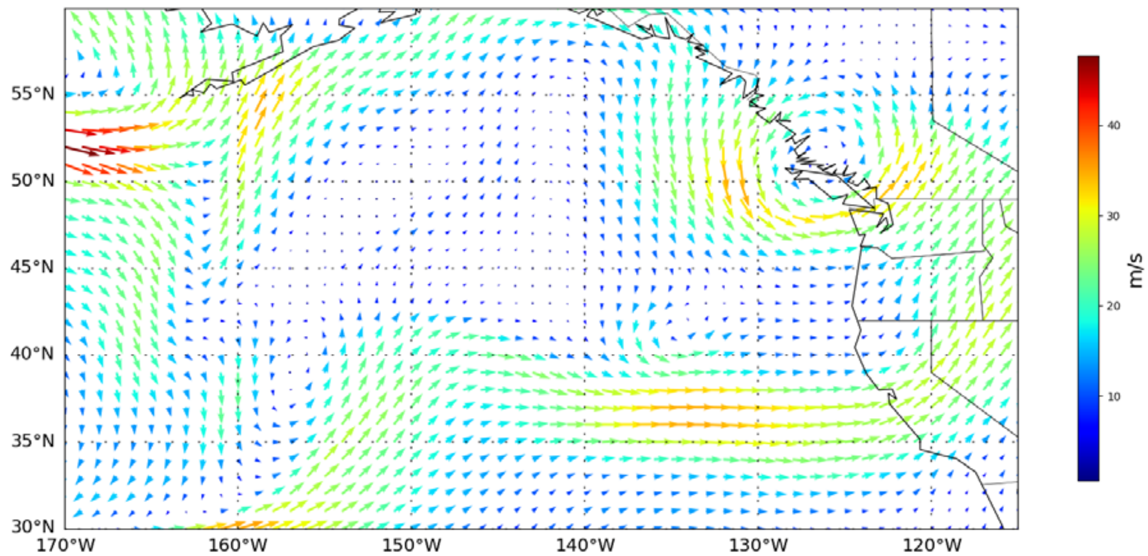

Figure 6. GFS modeled 250 hPa winds over the PacNW domain 08 05 2016 1800 z + 3 hr forecast.

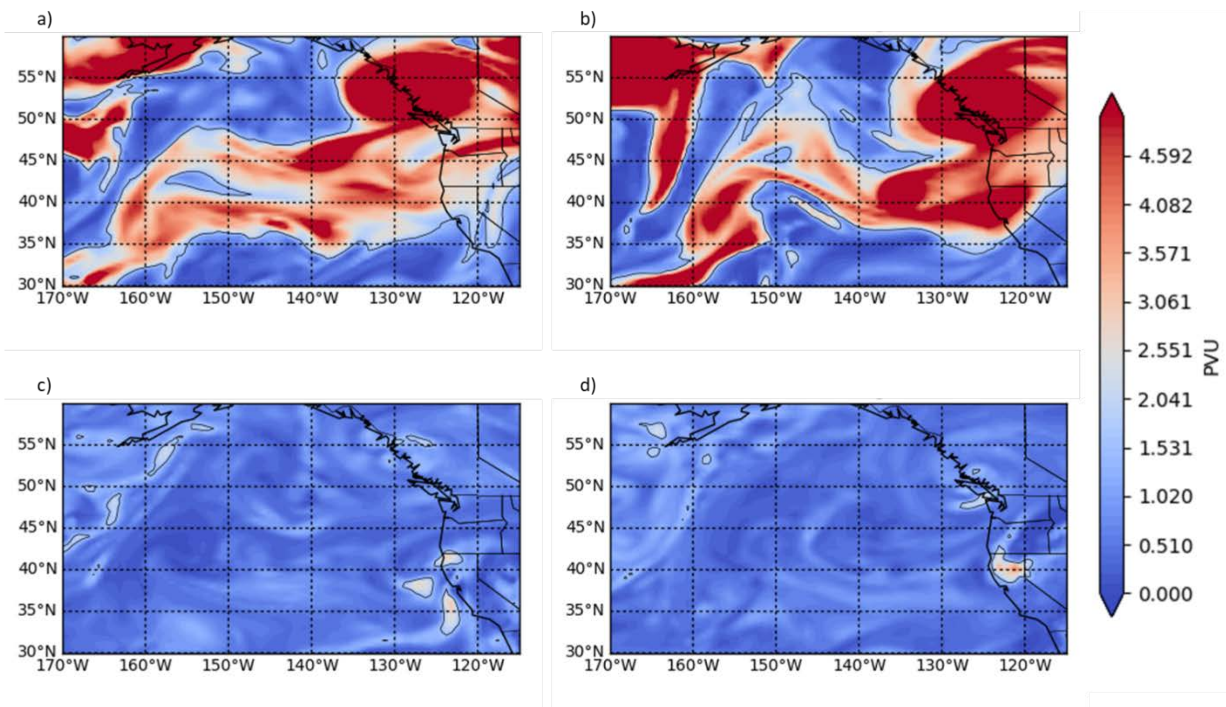

Figure 7. MERRA-2 PV 21z reanalysis data over the PacNW, colors plotted values 0 – 5 PVU, black line = 1.5 PVU a) August 4, 2016 at 11 km b) August 5, 2016 at 11 km c) August 4, 2016 at 5 km d) August 5, 2016 at 5 km.

the 21z afternoon hour. The bottom panels illustrate the progression of the stratospheric air mass eastward from off the west coast of California, to influence the region above most of Northern California by August 5, 2016. The intrusion into the middle-to-lower troposphere moved into Northern California from the west with the upper-level trough.

The third stratospheric intrusion event occurred early on August 9, 2016 within Northern California and remained present through just that date. The placement of the jet-stream across the PacNW was high, hugging the Gulf of Alaska for most of the domain (Fig 8). A large center of low-pressure occurred in the central region of the Southwest of the domain, with high-pressure to the northeast and to the northwest creating the large ridge of high pressure. This low-pressure developed from the low-pressure which diverted the jet-stream southward during the second intrusion event (Fig 6). The fastest wind speeds were near 50 m/s and were located just upstream from the positive tilted shortwave troughs, the important one to the event of interest being located over Northern California. With a center of low-pressure organized near the Washington, Idaho and Canadian boarders and an embedded shortwave, the coastal states were under the influence of low pressure. Of the three intrusion events, this one recorded the lowest surface pressure (SJSU CABOTS, 2016). The shortwave elongated the trough off the west coast of the Bay Area. This gave a positive tilt to the trough axis, and a large upper level-frontal region, perfect for tropopause folding.

The top panels of Figure 9 illustrate the MERRA-2 PV values at a height of 11 km, as with the previous two events. These indicate the association of higher PV values with the

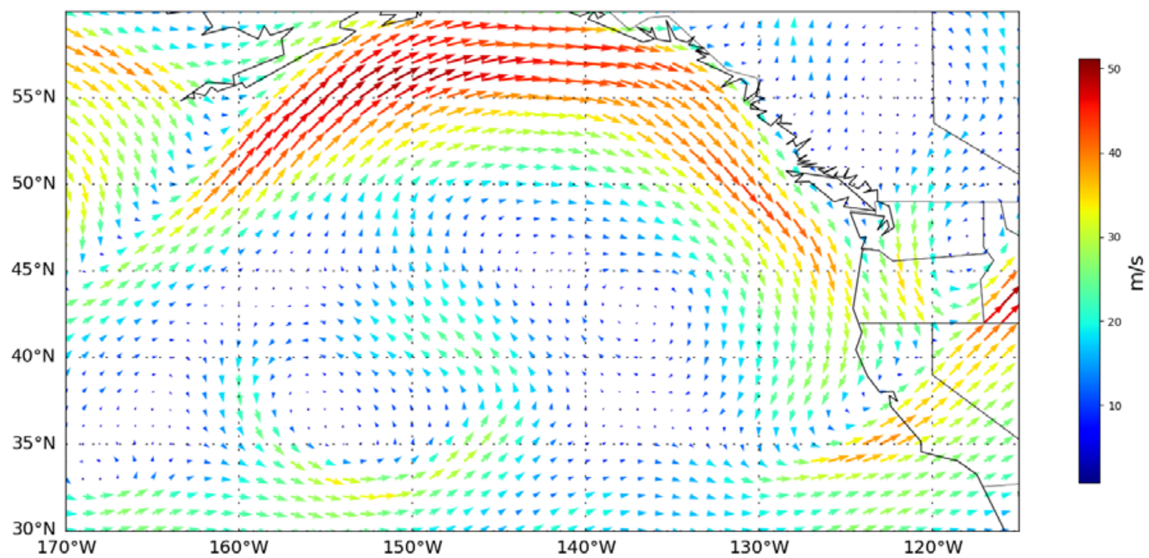

Figure 8. GFS modeled 250 hPa winds over the PacNW domain 08 09 2016 1800 z + 0 hr forecast.

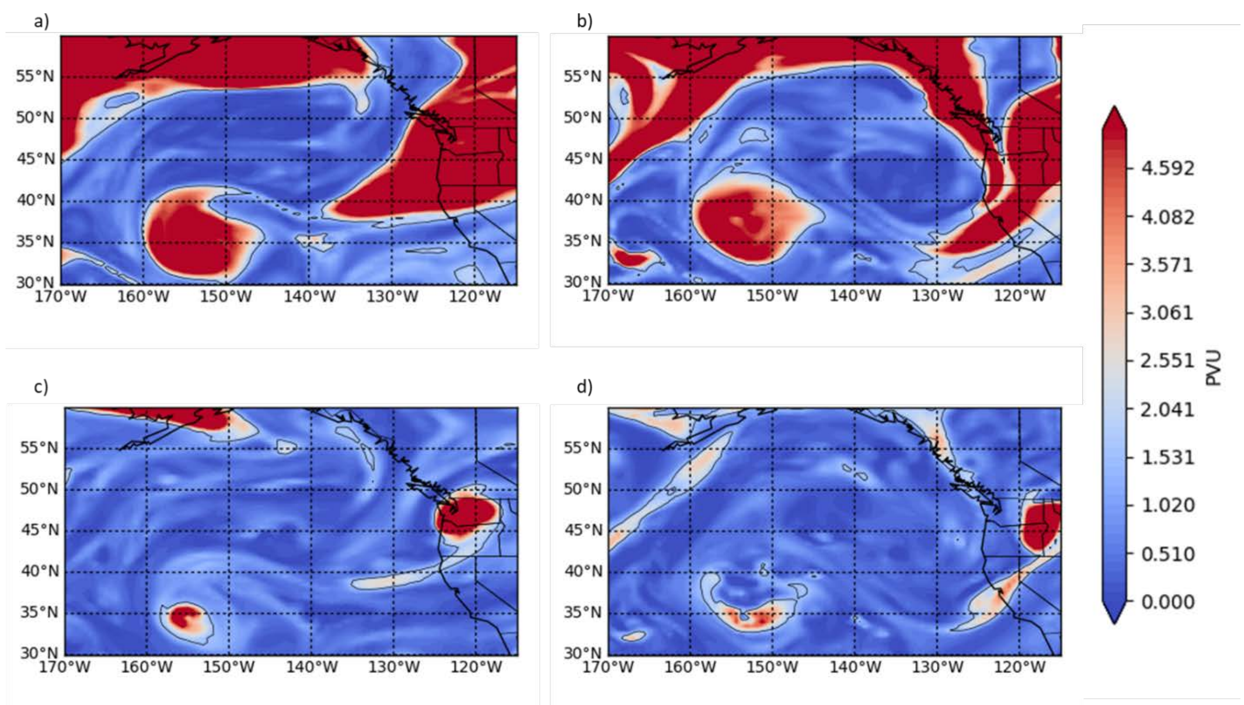

Figure 9. MERRA-2 PV 21z reanalysis data over the PacNW, colors plotted values 0 – 5 PVU, black line = 1.5 PVU a) August 8, 2016 at 11 km b) August 9, 2016 at 11 km c) August 8, 2016 at 9 km d) August 9, 2016 at 9 km.

previously described jet stream, jet streaks, upper-level fronts, and low-pressure systems during the third stratospheric intrusion event (Fig 8). The height of the tropopause over Northern California remained lowered, visible by a large spread of higher PV values as the upper-level front tracks southeasterly across California. The bottom panels of Figure 9 illustrate the deeper penetration of the stratospheric air mass at a height of 9 km over Northern California. The left panels of Figure 9 represent the MERRA-2 PV values for the date of August 8, 2016 at the 21z afternoon hour. The right panels of Figure 9 represent the MERRA-2 PV values for the date of August 9, 2016 at the 21z afternoon hour. The bottom panels illustrate the progression of the stratospheric air mass southeasterly to influence the region above the greater Bay Area, the State Capital, and Tahoe by the afternoon of August 9, 2016. The intrusion into the middle troposphere moved across Northern California with the progression of the elongated upper-level positively tilted trough.

During the defined time periods, the larger intrusions cross over and influence both the North Bay Area and the Sacramento Valley. These regions were further analyzed to show the similarity of the two regions, defining them as comparable.

Regions of Comparison

Two regions of comparison were defined as follows, one for the North Bay Area which includes Bodega Bay (BBY) and the second for the Sacramento Valley (SAC). Figure 10 is a map of the North Bay Area and the Southern Sacramento Valley, including the red boxes to highlight the two regions under comparison. The domain for the two regions were defined based on the resolution of MERRA-2 data, a 0.5° latitude x

0.625° longitude box. Both the BBY region and the SAC region (Fig 10) fall within a larger domain encasing a of latitude 38.0 °N and 39.0 °N, and a longitude of -123.125 °W and -121.25 °W. All the ozonesonde data captured during the case study period fell within the defined BBY region.

Over each individual domain, the calculated average value of PV, ozone, RH, and SH, were analyzed for each model level of interest for this study (Figures 11, 12, 13, 14). Model data from a vertical column beginning with the surface model level up to a height of near 15 km were utilized to compare the regions. The averages calculated are representative of this case study period: July 25, 2016 through Aug 13, 2016. Similar modeled values and patterns of all examined variables are noticeable when comparing the regions, especially above 2 km. Recall, there are three stratospheric intrusion events of interest which occur during the case study period and will be discussed further on a

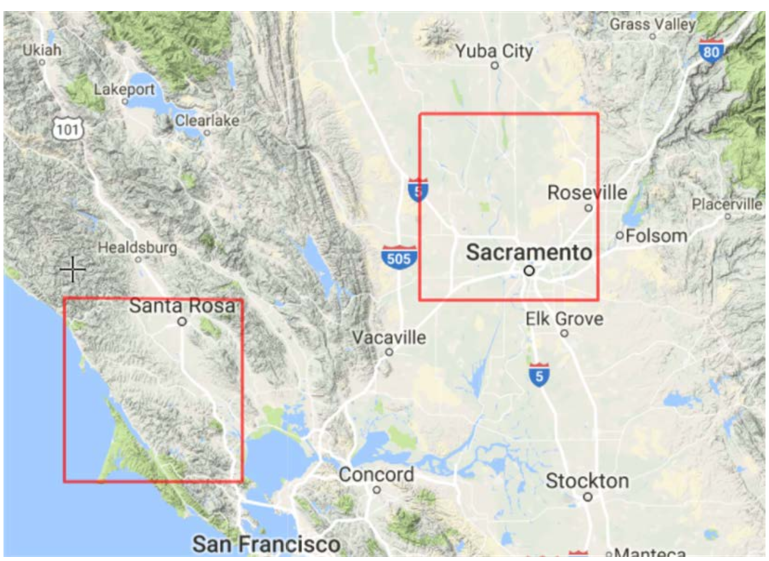

Figure 10. North Bay Area domain on the left and Sacramento Valley domain on the right. Modeled averages over these domains are used for comparison.

regional scale. The dates of the identified stratospheric intrusion events observed in the PacNW domain were as follows: July 27, August 5, and August 9.

A comparison of BBY average PV values (Fig 11a) to that averaged over the SAC region (Fig 11b) shows many similarities. This indicates that the average PV values above both regions behaved similarly, therefore so does the height of the tropopause. During the case study period, the tropopause height, defined by an outline of 1.5 PVU, varies from 10 to 14 kilometers. The height of the tropopause was observably higher during the first half of the case study period, lower during the second half, and experienced quite a bit of day to day variability. The 1.0 PVU outline marked the deep penetration of stratospheric air into the troposphere, including into the lower troposphere below 5 km. The same stratospheric intrusions, which penetrated into the middle and upper troposphere previously noted over the PacNW domain (Figs 5, 7, 9), are recognizable in both vertical columns concurrently (Fig 11, black circles). Though this study only focuses on three individual injections of stratospheric air masses, multiple occur during the case study period which inject into many different layers of the troposphere.

The first intrusion event under investigation began mid-day on July 27, 2016 (Fig 11) and remained present over both regions throughout the day of July 28, 2016. This intrusion occurred as a stratospheric air mass from a relatively high tropopause height of near 14 km, penetrates downward and injects through to near 7 km. The intrusion has passed through the BBY and SAC regions by the early hours of July 29, 2016.

The second intrusion event for examination happened on August 5, 2016. Beginning on August 4, 2016 the tropopause heights lowered to near 8 km (Fig 11). The strongest indication of stratospheric influence occurred during the latter hours of August 5, 2016 within the 10 – 12 km as PV values increased with a much stronger gradient. Engulfed in

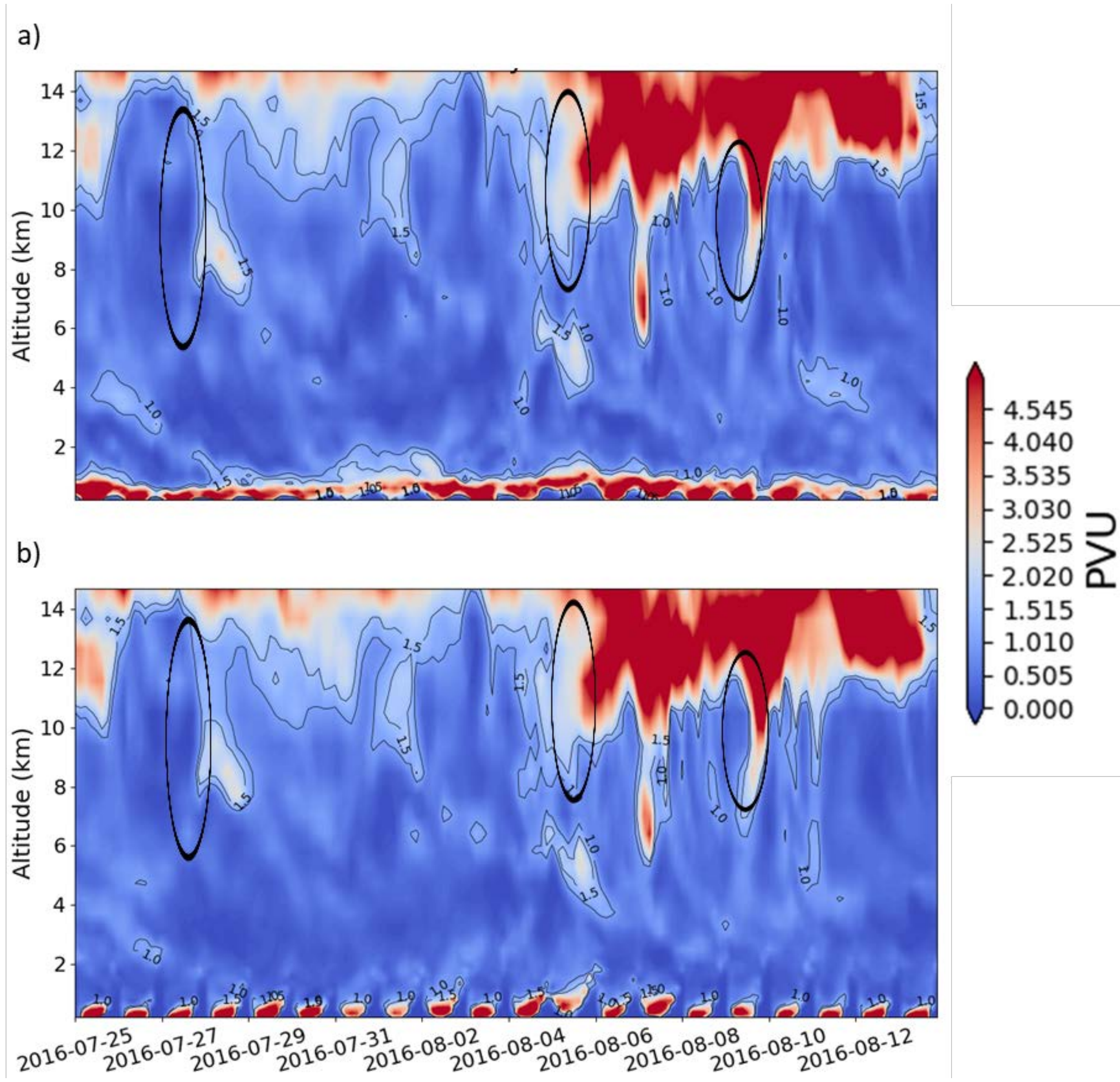

Figure 11. Average domain values for July 25 through August 13, 2016 for the lowest model level up to 15 km, PV: values 0 – 5 PVU, blackline = 1.5 PVU, 1.0 PVU, a) North Bay Area b) Sacramento Valley.

the 4 – 7 km region of the troposphere is a cut-off of higher PV, a sign of stratospheric air mass injection. This air mass noticeably progresses downward with time. It began located near 7 km on August 4, 2016 and stretches downward with time, to influence the column of air near 4 km during the early hours of August 6, 2016.

The third intrusion event of interest occurred on August 9, 2016 and was quick moving driven by the upper-level front. As with the second intrusion event, the height of the tropopause was relatively low, being near 11 km (Fig 11). This stratospheric air mass penetrated deeper into the troposphere in the earlier hours of the date, approaching as low as 6 km. By the afternoon hours, much of the intrusion remained above 8 km. By the end of the date, the upper-level front had passed through the region, restoring the height of the tropopause to near 10 km.

The modeled average ozone concentrations for the case study period within the 15 km vertical column above BBY and SAC are visible from Figure 12a, 12b. In the tropopause region, the ozone values in the first half of the case study period are lower in concentration in association with the higher PV-defined tropopause heights. During the second half of the case study period the ozone concentrations were greater in association with the lower PV-defined tropopause heights. The ozonesondes launched at BBY captured high ozone concentrations (Fig 2b) in correspondence with the events captured in the MERRA-2 reanalysis data (Fig 11). Similar features are noticeable in the modeled MERRA-2 reanalysis ozone data. Notice that the color scheme of Figure 12 is the same as that for measured ozone at BBY, yet the concentration range is quite different. The modeled ozone shows a concentration range of 50 – 250 ppb. Recall that Figure 2b shows measured ozone observed at BBY during the afternoon hours and includes the modeled case study period. The ozonesonde data are represented with a scale ranging from 0 – 150 ppb. Also recall that these values observed at BBY were collected during the peak concentration hour of high surface ozone. The differences between the BBY

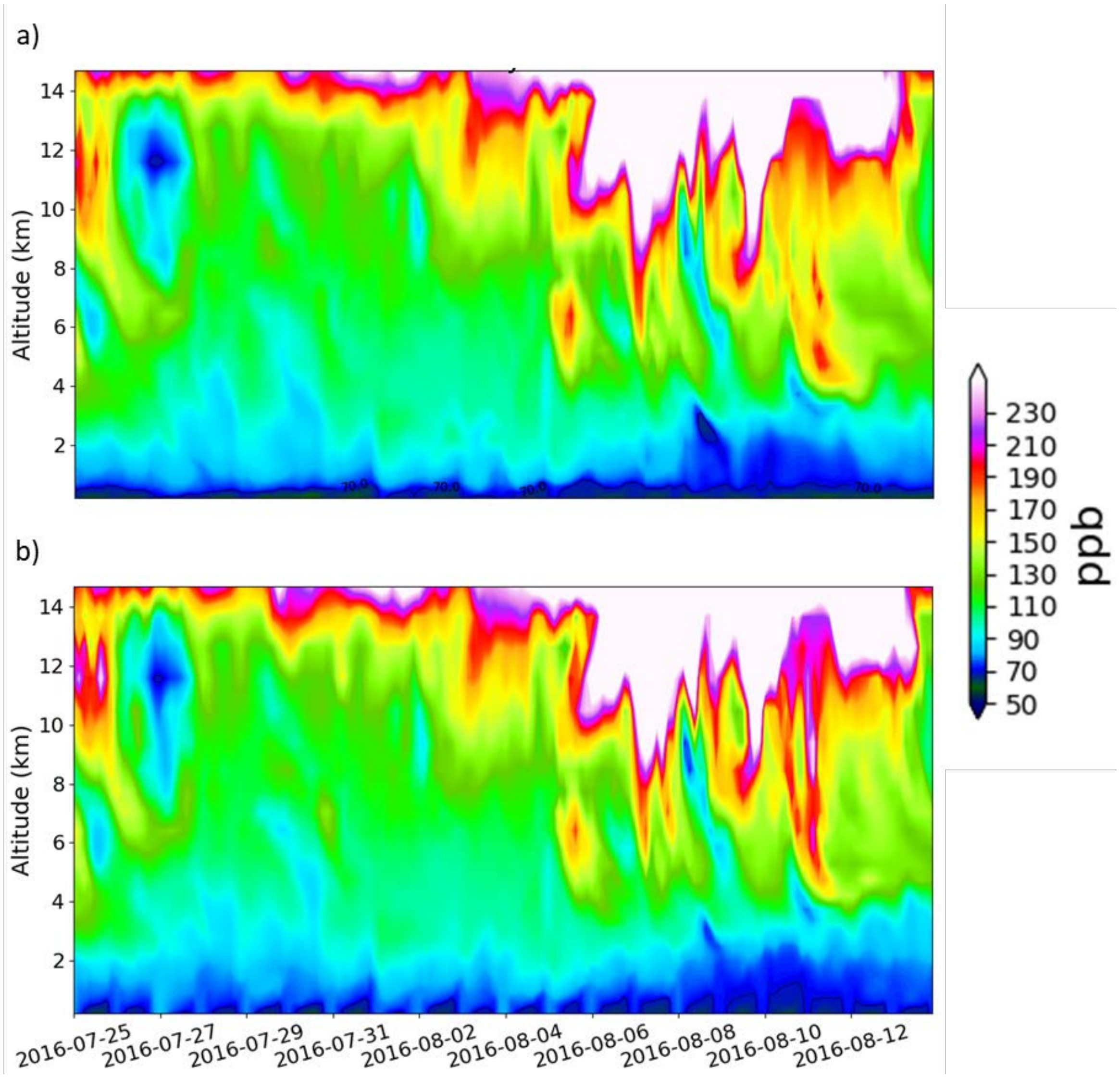

Figure 12. Average domain values for July 25 through August 13, 2016 for the lowest model level up to 15 km, Ozone: values 50 – 250 ppb, blackline = 70 ppb, a) North Bay Area b) Sacramento Valley.

ozonesonde data and the modeled reanalysis MERRA-2 data shows the importance of obtaining stronger boundary conditions in our modeling systems for coastal regions.

Relative humidity MERRA-2 reanalysis data for the case study period is visual in Figure 13. Patterns within the RH data for both locations differ from the beginning half

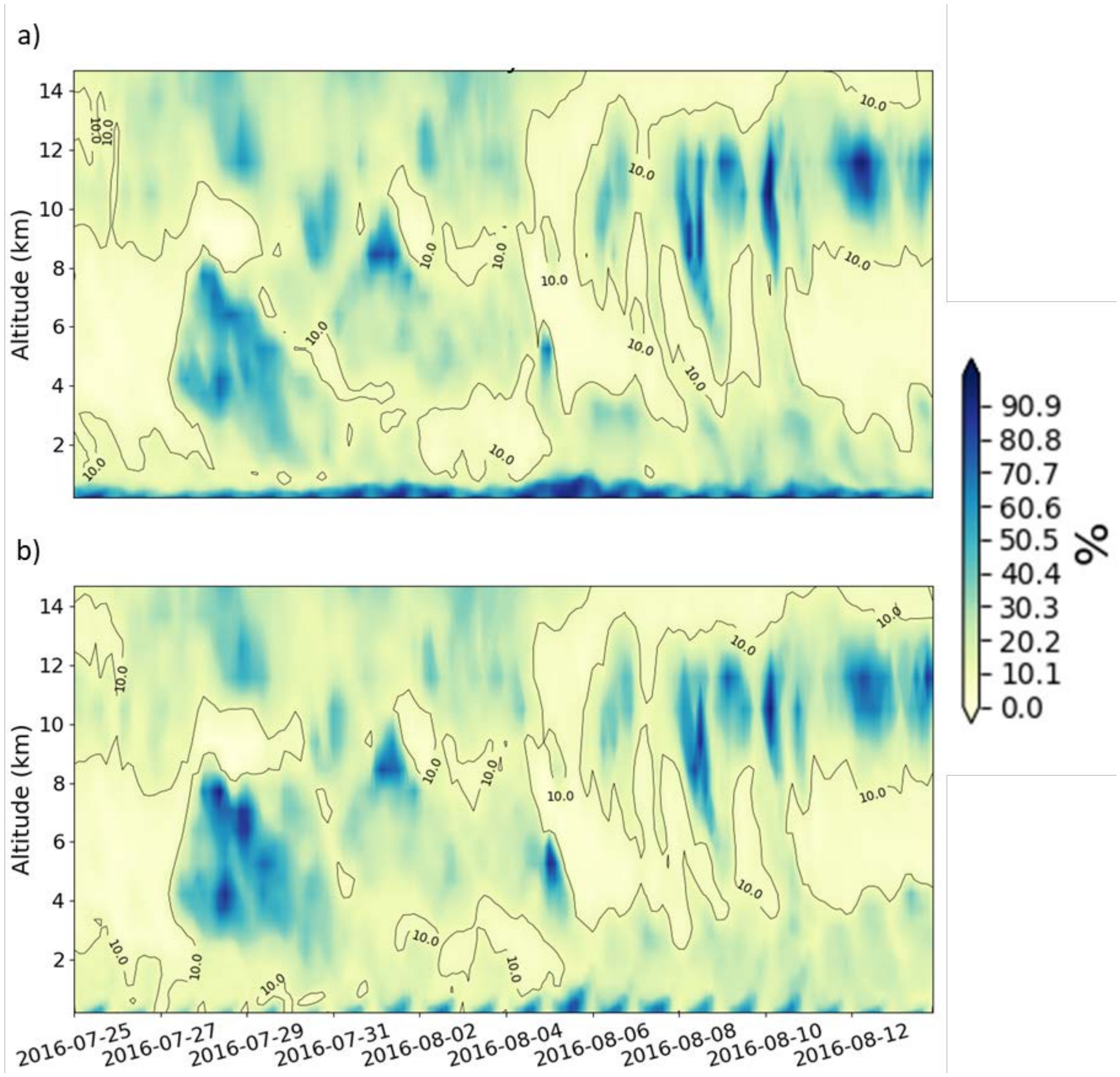

Figure 13. Average domain values for July 25 through August 13, 2016 for the lowest model level up to 15 km, RH: values 0 – 100 %, blackline = 10 %, a) North Bay Area b) Sacramento Valley.

of the case study period to the second half (Fig 13), similar to PV and ozone. During the first few days, the 2 – 8 km vertical column of air remained quite dry, under 10 % RH. As the surge of moist air in the 3 – 8 km vertical column begins on July 27, the drier air disperses to greater and lower altitudes. At the beginning of the case study period, clear dry pockets of air influence below 2 km. These extend to the surface over the SAC region and remain slightly elevated above the shallow marine layer at BBY, being most pronounced at both locations during July 29 through July 31, 2016. A moist air mass then influenced the lowest 2 km for a few days. From August 1 through August 5, 2016, in the 1 – 5 km vertical column, a dry air mass of less than 10 % became influential above both regions. August 5, 2016 marks the beginning of the second half of the case study period (Fig 13). The moisture in the lower 2 km remains greater than 10% RH. The only exception occurred at BBY on August 7, 2016. The drier air masses remain elevated within the 3 – 8 km, and at the top of the vertical column within the 12 – 15 km. It is important to note the extent of dry air throughout most of the vertical column, 3 – 13 km, which occurred on August 5, 2016.

A visual is given to the SH MERRA-2 reanalysis data for the case study period in Figure 14. The much drier air is represented by a color of aqua blue, and the air with a higher water vapor content is magenta in color. This figure includes 2 blacklines to mark the SH tropopause. As with the PV-defined tropopause heights, the SH values can be thought of that which show the tropopause height and the value which represents the deep penetration of stratospheric air. A value of 0.05 g/ kg represents the SH-defined tropopause for the case study period. The 0.15 g/kg SH line shows the deeper penetration of stratospheric air, similar in structure of the PV-defined tropopause (Fig 11).

The surge of moisture into the 3 – 8 km vertical column above both regions on August 27, 2016 is clear (Fig 14). Along with this instance came the rising of the 0.15

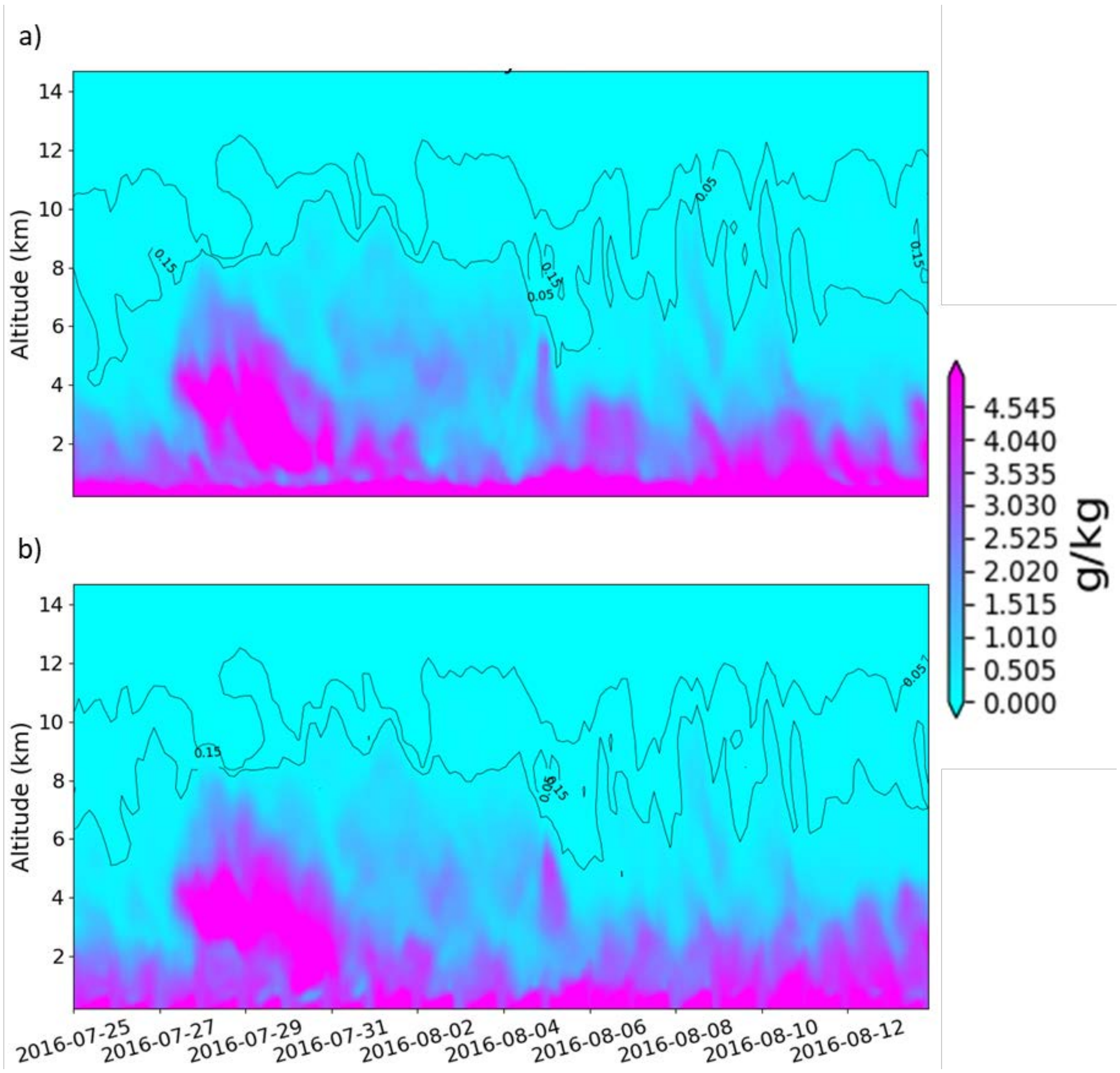

Figure 14. Average domain values for July 25 through August 13, 2016 for the lowest model level up to 15 km, SH: values 0 – 5 g/kg, blacklines = 0.05 g/kg and 0.15 g/kg, a) North Bay Area b) Sacramento Valley.

g/kg line from the 4 – 6 km vertical column to above 8 km. Yet also a lowering of the 0.05 g/kg line from near 11 km to near 8 km occurred simultaneously. As within the RH data, pockets of generally low SH values were influential in the lower 1 km vertical column above both regions on July 29 through July 31, 2016. Figure 14 also indicates a lowering of the 0.15 g/kg SH line. Beginning on August 4, stratospheric air began to penetrate lower into the atmosphere, reaching near 7 km on the 5th of August. For the rest of the case study period there are multiple oscillations to the height of the SH-defined tropopause, including the lowering near 6 km on August 9, 2016.

The comparison of the average reanalysis data over each of the two domains gives a promising outcome. From the comparison of MERRA-2 PV, the same stratospheric intrusions of interest are noted above BBY and SAC (Fig 11). When evaluating the MERRA-2 average ozone, both BBY and SAC were similar in structure to the placements of the higher and lower ozone concentrations (Fig 12). The moisture observed throughout the vertical column above both the BBY and SAC region follow similar large pattern structure (Fig 13). The injection of stratospheric air traced by the 0.15 g/kg SH value shows very similar depths in to the air above both the BBY and SAC regions (Fig 14). This analysis indicates that the air masses above both regions are similar in nature, especially above 2 km, and are comparable. Therefore, ozonesonde measurements obtained throughout the BBY vertical column would give an indication of ozone structure in the vertical column above SAC.

CABOTS data

The daily variation of ozone by height was evaluated to visualize the downward progression of these dry stratospheric air masses rich in high ozone concentrations. This was done through the evaluation of the daily percent change in ozone from one day to the next throughout the 15 km vertical air column. Figure 15 shows the daily percent changes for BBY measured ozone for the case study period. Multiple scales are required to distinguish smaller changes which occur in the middle and lower troposphere. The daily changes in ozone within the boundary layer are much smaller than those changes within the region of the tropopause. Therefore, the vertical column was divided into three sections for a better visual representation: the upper troposphere (Fig 15a), the middle troposphere (fig 15b), and the lower troposphere (fig 15c). Each of the previously defined stratospheric intrusion events were further analyzed to give insight into the downward progression of increasing ozone with time.

Figure 15a is used in the investigation of ozone variability throughout the 10 – 15 km vertical column, or the region of the upper troposphere, tropopause, and lower stratosphere. The substantial changes in ozone associated with the variable tropopause heights are noticeable with the broad scale range of -150 – 450 % change in ozone. Daily variations in ozonesonde data for the stratospheric intrusion dates of interest are further discussed.

From July 26 to July 27, 2016 an increase of ozone was observed through a long vertical column between 6 – 14 km above sea level (Fig 15a). This observed increase

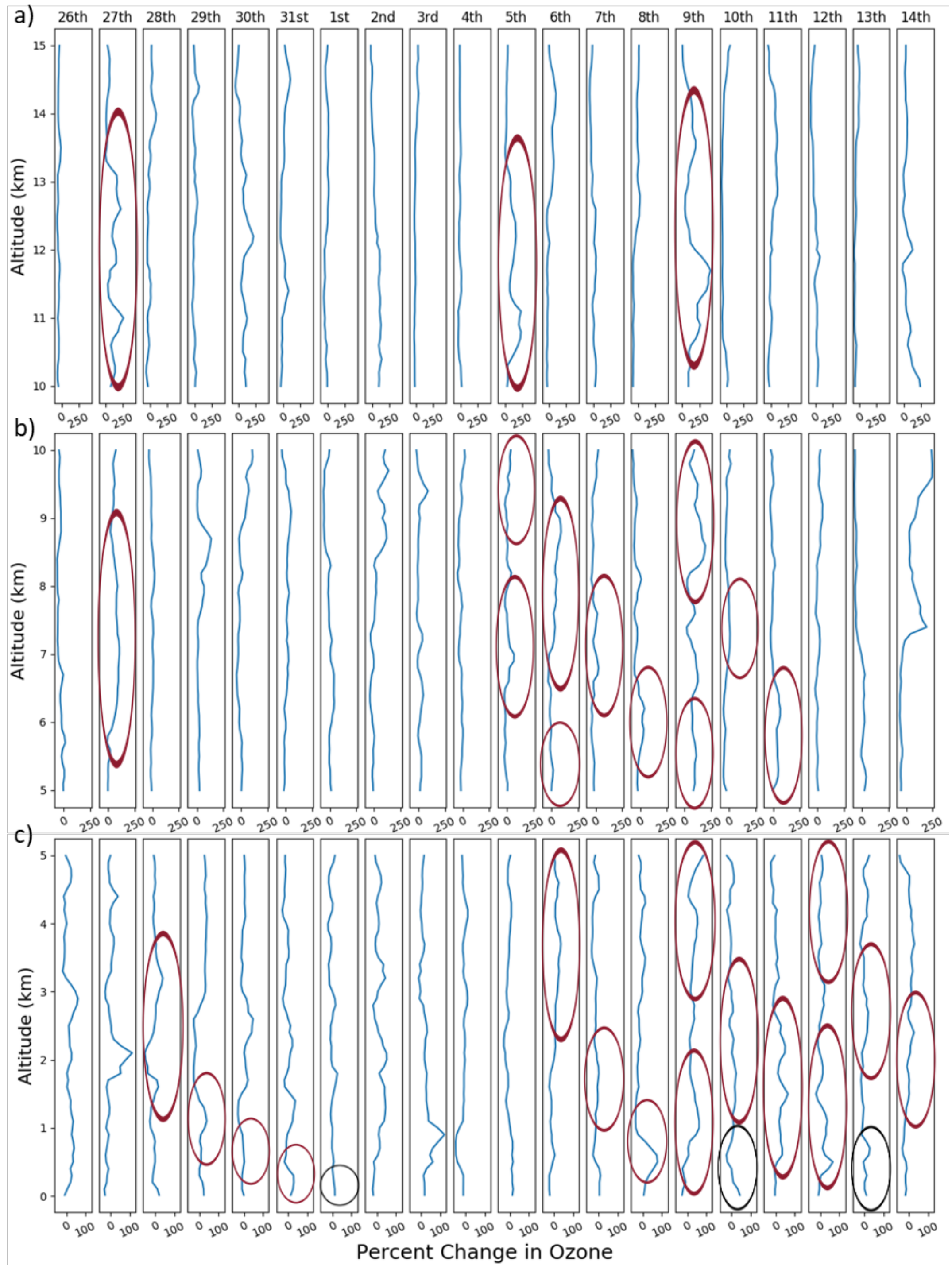

Figure 15. Calculated percent change in observed daily ozone along the SJSU BBY Ozonesonde vertical profile 15 km column from one day to the next, July 26 through August 14, 2016. a) Scale: -150% to 450%. b) Scale: -100% to 300%. c) Scale: -50% to 150%.

indicates that the ozonesonde acquired measurements at the beginning of the first stratospheric intrusion event of interest. The greatest change within the column was observed at 10.9 km, with an increase in ozone of 258%. At this altitude, the ozonesonde measured a value of 86 ppb on July 27, 2016.

From August 4 to August 5, 2016 an increase of ozone was observed through the 7 – 14 km vertical column above sea level (Fig 15a). An indication of capturing measurements during the second intrusion event of interest. The greatest daily change in ozone within the vertical column was observed at a height of 11.0 km as the ozone increased by 236% from the day prior. The ozonesonde measured a value of 198 ppb at 11.0 km on August 5, 2016.

From August 8 to August 9, 2016 an observed increase in ozone occurred throughout most of the vertical column, excluding the upper and the lower one kilometer. The greatest of all the percent daily changes in ozone was observed from August 8 to August 9. An increase of ozone by 415% was observed at a height of 11.1 km, with an ozonesonde measurement of 169 ppb on August 9, 2016. From each of the three events, the positive daily change in ozone was tracked to the lower levels of the troposphere, including the surface.

During the first stratospheric intrusion, the tropopause was relatively high. Therefore, the main interest of the intrusion came from the increases in ozone that occurred in association with the cut-off high PV in the MERRA-2 reanalysis data beginning on July 27, 2016 (Fig 11). The 6 – 8 km of the vertical column above BBY experienced increases in ozone ranging from 90 – 110 % (Fig 15b). The ozone concentration changed from near 40 ppb to near 80 ppb. Progressing with time, on July 28, ozonesonde measurements captured an increase of ozone in the 1.5 – 4 km of around 50% from the day prior (Fig 15c). Moving forward with time to July 29 and to July 30, the downward progression of this stratospheric air became slower. By July 31, this air mass with stratospheric ozone influence is impacting concentrations below 2 km, reaching the lower 1 km by August 1, 2016 (Fig 15c).

During the beginning of the second half of the case study, a similar downward progression of measured increasing ozone with time was clear. This marks the second intrusion event of interest. Recall that the MERRA-2 PV defined intrusion penetrates from a relatively low tropopause deep into the middle troposphere (Fig 11). This begins with an observed increase in ozone concentration, from August 4 to August 5, 2016 as previously discussed (Fig 15a). On the same date, at the 7 km region, a clear increase in ozone concentrations of near 100% is observed (Fig 15b). Both portions of the intrusion are tracked downward, impacting the surface ozone concentration on two dates. Comparing August 5 to August 6, within the column of air measured, ozone increases are recognizable in the 7 – 9 km region. Smaller increases occur within the 3 – 5 km region (Fig 15c). Following the upper air mass steadily downward, by August 8 the increases in observed daily ozone had progressed downward, impacting concentrations within the 5 – 7 km region. The ozone which originated with the cut-off of high PV near 7 km, by August 8 has influence on the ozone concentrations in the lower 1 km of the air column. By August 10, 2016 a recognizable increase in ozone near 50% occurred at the lowest levels of the vertical column.

On August 9, 2016 the third intrusion event of interest began as stratospheric air was injected into the middle troposphere (Fig 11). Along with this event came a heavier push to the downward progression of the previous stratospheric air mass tracked, along with further stratospheric ozone influence in the upper column of air (Fig 15). The second stratospheric air mass, which began influencing upper-level ozone concentrations on August 5, has now progressed down with time to influence the ozone concentrations within the 3 – 6 km vertical column. By August 10, 2016 the air mass which originated near the tropopause on August 5, now began to influence the ozone concentrations within the 1 – 3.5 km vertical column. A steady downward trend of increasing ozone can be followed towards the marine boundary layer, impacting the surface ozone concentration by August 13, 2016 (Fig 15c). At this time, stratospheric ozone associated with the upper-level intrusion into the middle troposphere on August 9, 2016 has progressed downward with time, influencing the ozone concentrations within the 1 – 3 km region by August 13, 2016.

Both the first and second stratospheric intrusion cases exhibit a 6-day downward progression of ozone transportation from the commencement of the intrusion into the middle troposphere, to influencing the surface ozone concentrations at BBY. This is captured in the ozonesonde data and is recognizable in the surface ozone monitoring data onsite provided by BAAQMD (Fig 16). To reduce the effects of local pollution on the surface monitoring values (Parrish et al. 2010), the maximum daily 8-hour average ozone surface values were calculated and investigated. As previously stated, this average ozone value is one of importance to the EPA set NAAQS.

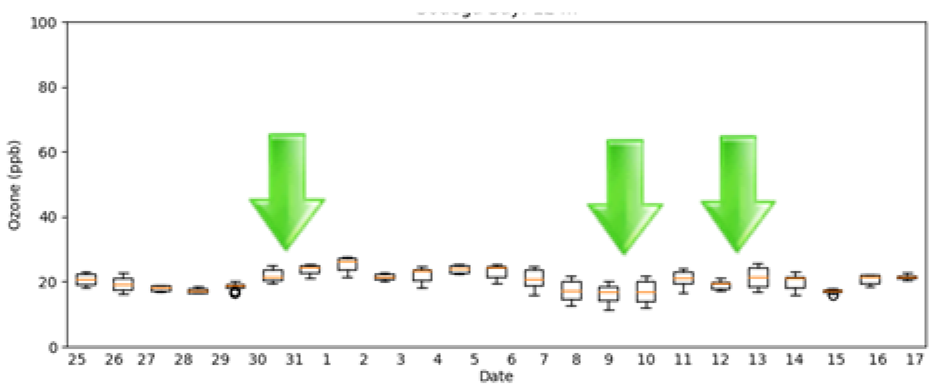

Figure 16. Classic box plot for the calculated Maximum Daily 8-hour Average ozone at BBY for July 25 through Aug 17, 2016, local hour 0 through 23.

The observed ozone increases in the lowest levels of the vertical profile captured by BBY ozonesonde measurements match up nicely with the observed increases in surface ozone concentrations at BBY. The green arrows in Figure 16 indicate the dates on which the stratospheric ozone influenced the surface ozone concentrations. From July 30 through August 1, 2016, a clear increase in the mean maximum daily 8-hour average values of surface ozone were observed (Fig 16). A secondary increase in surface maximum daily 8-hour average ozone values occurred from August 9 through August 11, 2016. Though the mean ozone value for the date remains similar from August 9 to August 10, the daily range of ozone values were greater on August 10. A third distinguishable increase in surface ozone occurred from August 12 to August 13, as both an increase to the mean observation and the daily range of concentrations. These increases in surface ozone line up nicely with the stratospheric air influence at the surface observed through BBY ozonesonde data and MERRA-2 PV reanalysis data. Also evident from Figure 16, the observed maximum daily 8-hour average ozone concentrations at BBY illustrate a small daily range of less than 10 ppb. The mean value of maximum daily 8-hour average ozone observed at BBY during the case study period was near 20 ppb, represented by the orange lines (Fig 16).

Surface Maximum Daily 8-hour Average Ozone

This study calculates the surface maximum daily 8-hour average ozone at fourteen different ozone surface monitoring stations located in the southern Sacramento Valley and the local lower Sierra Nevada Foothills. Most of the surface stations fall within the SAC domain (Fig 3). A few stations are located slightly outside, displaced locally to the North, to the South, and to the East. Most of the surface monitoring sites in the SAC area are included in the Sacramento Valley non-attainment zone except for the Grass Valley monitoring site, which is included in a different non-attainment zone. Table 1 gives a list of the surface monitoring sites used, along with the latitude and longitude, and elevation above sea level. The sites are listed in descending order from the highest elevation to lowest elevation in meters above sea level.

For further analysis of regional surface ozone, the monitoring sites in the Sacramento Valley were subcategorized into three groups based on elevation; high, mid, and low. These were defined accordingly: surface stations located above 108 meters, located between 108 meters and 47 meters, and located below 47 meters. Both the high and low categories include five surface stations each, while the mid is comprised of four monitoring sites. This also conveniently groups the surface ozone monitoring sites similarly by longitude. The high elevation surface sites are located furthest East while the low elevation surface sites are located farthest West (Fig 3).

Table 1. Surface Ozone Monitoring Sites

Name	**Latitude (°N)**	**Longitude (°W)**	**Elevation a.s.l. (m)**
Grass Valley	39.23352	121.05567	865
Colfax	39.09979	120.95391	738
Placerville	38.72528	120.82192	612
Cool	38.89094	121.00337	473
Auburn	38.93568	121.09959	434
Folsom - Natoma	38.68329	121.16444	108
Roseville	38.74643	121.26498	60
Sloughhouse	38.49444	121.21115	59
Lincoln	38.88559	121.30199	47
North Highlands	38.71209	121.38108	33
Del Paso	38.61374	121.36801	30
Davis	38.53455	121.77340	19
T - Street	38.56844	121.49311	15
Bodega Bay	38.31869	123.07197	12
Elk Grove	38.30256	121.42083	7

The mean maximum daily 8-hour average ozone observations were compared among all the surface monitoring sites. Ozone observations at the inland SAC surface sites generally were greater than that observed at BBY and were representative of a larger daily range in ozone. A mean maximum daily 8-hour average ozone of near 70 ppb was observed during the case study period at Grass Valley. Similarly, mean ozone concentrations observed at the Colfax and Placerville sites were around 70 ppb for the case study period (Fig 17). This observation alone creates a clear picture for the non-attainment and unhealthy surface air conditions during the period of interest. The lower two high elevation surface monitoring sites, Cool and Auburn, experienced lesser mean maximum daily 8-hour average ozone concentrations of around 60 ppb (Fig17). In general, during the case study period, the mean ozone concentrations were observed to be greatest at the highest elevation site and decrease with a corresponding decrease in height

(Fig 17). This same general pattern is noticeable throughout the data observed at both the mid and the low elevation category sites. The mid monitoring sites observed mean ozone concentrations for the period ranging from 40 – 50 ppb (Fig 18). The low monitoring sites observed mean concentrations ranging from 30 – 40 ppb (Fig 19). All these values being greater than the mean maximum daily 8-hour average ozone observation at BBY, a value near 20 ppb (Fig 16).

The daily range in ozone observed at the high elevation surface sites were evaluated and compared to that observed at BBY. At first glance the maximum daily 8-hour average ozone observations at the high category sites (Fig 17), were obviously much different from that of BBY surface observations (Fig 16). Concentrations observed at Grass Valley were much higher than that observed at BBY. The Grass Valley surface ozone monitoring site is located at 865 meters above sea level, the greatest in elevation among all the sites. Of all the fourteen SAC surface monitoring stations, Grass Valley exhibited the smallest daily range of maximum daily 8-hour average ozone values, most similar to that of BBY. All sites within this high elevation category have a broader daily range of ozone concentration values than that observed at BBY. For example, on the first day of the case study period, July 25, 2016, the daily range of concentrations was near 40 ppb for the high monitoring sites, Grass Valley being the exception with a daily range in ozone closer to 20 ppb (Fig 17). These ranges easily quadruple the daily range in maximum daily 8-hour average ozone found at BBY of little over 5 ppb.

The daily range of calculated maximum daily 8-hour average ozone at the mid category sites were compared with the daily ranges at higher and lower elevations. In general, those monitoring stations located in the mid elevation region had the greatest daily range of maximum daily 8-hour average ozone values, seemingly being influenced from the air above and below. Again, observations on July 25, 2016, the mid elevation sites exhibited daily ranges of ozone greater than 40 ppb and approached 80 ppb. Figure 18 gives indication that the daily range of ozone at the mid elevation sites exhibit a wider

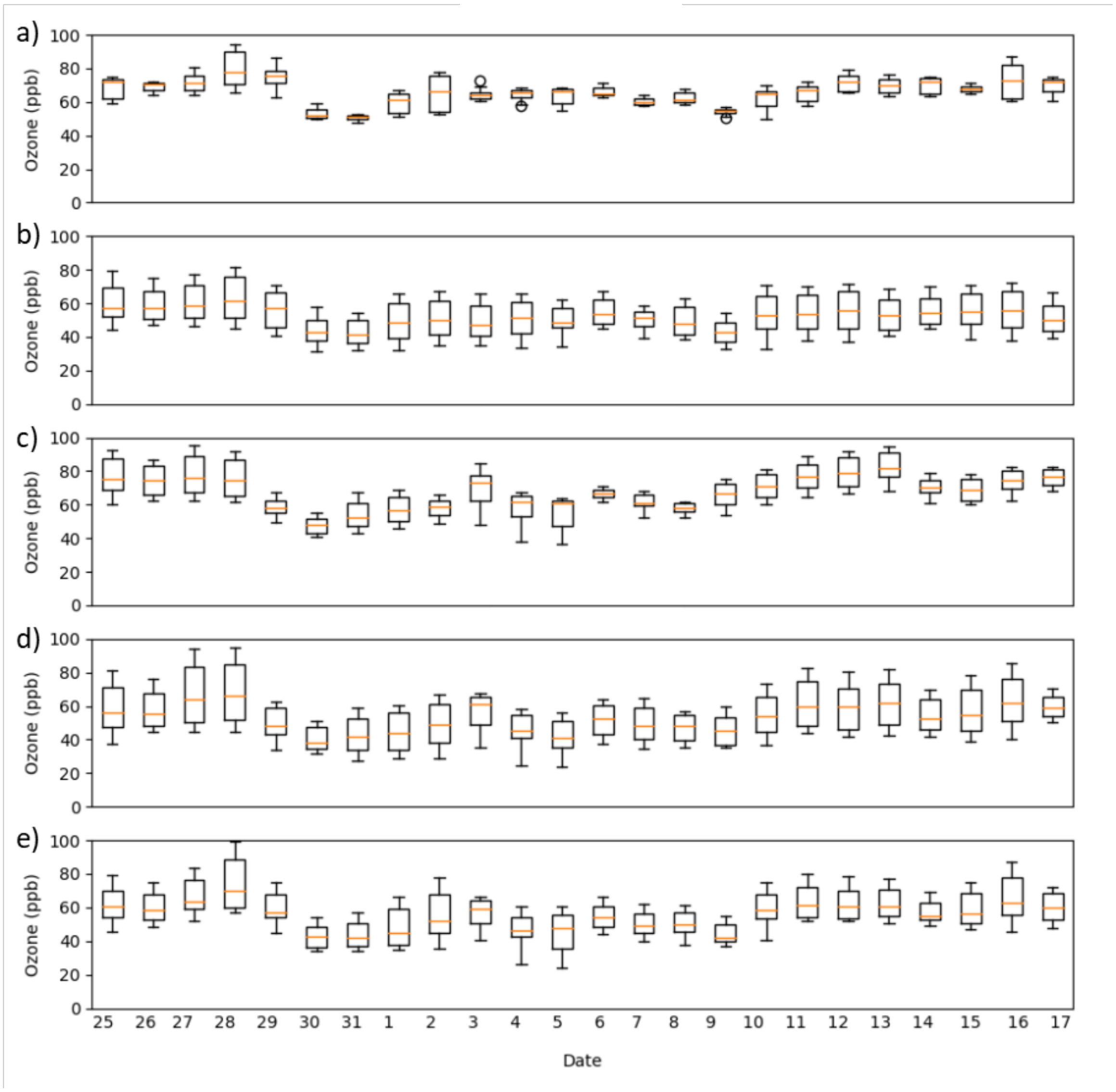

Figure 17. Calculated Maximum Daily 8-hour Average surface ozone concentration box plots for July 25 – August 17, 2016 for high elevation sites, orange bar = daily mean ppb, a) Grass Valley b) Colfax c) Placerville d) Cool e) Auburn.

spread when the high elevation sites exhibit a mean daily value that was above the average for the case study period. An example would be as that observed on July 27, 2016 (Figs 17, 18). Also, the opposite appears to hold true. If the high elevation sites exhibited a mean concentration that was below the mean concentration for the selected case study period, then the daily range observed at the mid elevation sites were generally

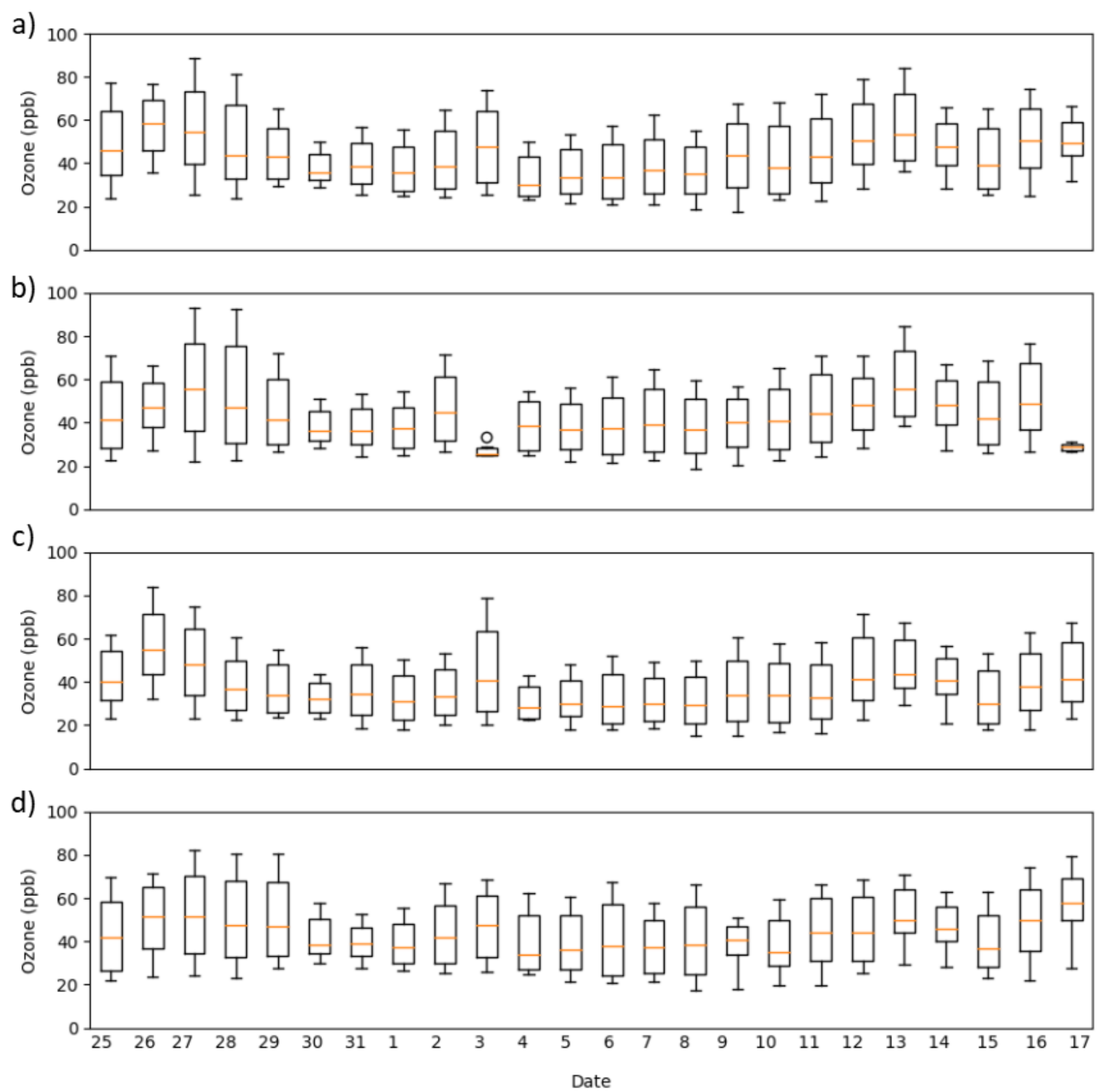

Figure 18. Calculated Maximum Daily 8-hour Average surface ozone concentration box plots for July 25 – August 17, 2016 for mid elevation sites, orange bar = daily mean ppb, a) Folsom - Natoma b) Roseville c) Sloughhouse d) Lincoln.

lesser. An example occurred on August 1, 2016. On this date the Placerville site observed a mean value near 60 ppb, less than the mean value for the period. On this date the Lincoln station observed a maximum value near 60 ppb. Similarly, the minimum ozone value of the maximum daily 8-hour average ozone concentration within the mid category sites were greater or lesser based on the mean concentrations observed at BBY

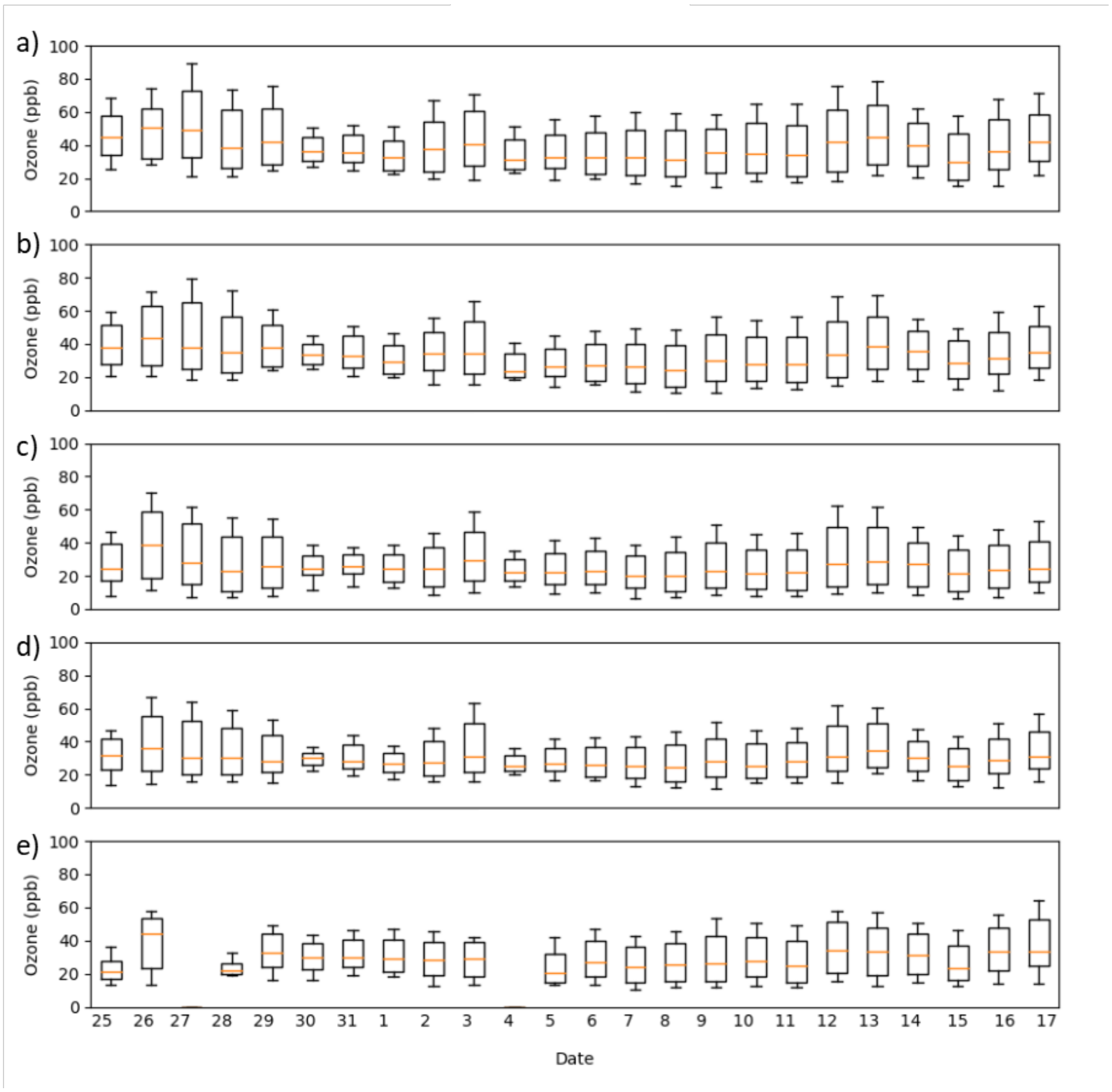

Figure 19. Calculated Maximum Daily 8-hour Average surface ozone concentration box plots for July 25 – August 17, 2016 for low elevation sites, orange bar = daily mean ppb, a) North Highlands b) Del Paso c) Davis d) T-street e) Elk Grove.

(Fig 16) and those observations at other lower elevation SAC surface sites. This gives an indication of how this mid elevation air layer is mixed and influenced with the air masses above and below.

The low elevation surface monitoring sites calculated maximum daily 8-hour average ozone values are compared with that calculated for BBY. The mean maximum daily 8-hour average ozone values among the low category sites were close to that observed at the BBY surface monitoring station (Fig 19). The two highest low category surface sites located near 30 meters in elevation, North Highlands and Del Paso, exhibit minimum values of maximum daily 8-hour average ozone similar to those observed at BBY (Fig 16). Interestingly, the minimum values in the daily range though can be substantially less than that observed at BBY. Closer examination of the maximum daily 8-hour average ozone values observed at Davis gives a good example (Fig 19). The Davis SAC surface monitoring site, being located farthest West and at an elevation of 19 meters above sea level (Fig 3, Table 1), displayed minimum ozone concentration observations as low as 5 ppb. Minimum values calculated remain under 20 ppb during the case study period, and near 10 ppb. These were the lowest observed ozone concentrations among all the sites (Figs 17, 18, 19). Recall that the mean maximum daily 8-hour average ozone values at BBY were near 20 ppb, with minimum values trending above 15 ppb (Fig 16).

An analysis of the lowest elevation surface monitoring site ozone concentrations gives insight into the differences between coastal and inland sites of similar elevation and latitude. Elk Grove being the lowest elevation among all the sites at 7 meters, still possesses a substantially greater daily range of maximum daily 8-hour average ozone

Table 2. Correlation Coefficients for Calculated Maximum Daily 8-hour Average Ozone, the highlighted values represent the strongest correlation for each station with a station located elsewhere.

Correlation Coefficent	BBY	Elk Grove	T-street	Davis	Del Paso	North Highlands	Lincoln	Sloughhouse	Roseville	Folsom-Natoma	Auburn	Cool	Placerville	Colfax	Grass Valley
BBY	1.000														
Elk Grove	***0.385***	1.000													
T-street	0.260	0.943	1.000												
Davis	0.247	0.941	***0.967***	1.000											
Del Paso	0.241	***0.948***	***0.980***	0.954	1.000										
N. Highlands	0.226	0.914	0.957	0.945	***0.967***	1.000									
Lincoln	0.200	0.907	0.916	0.885	0.924	0.921	1.000								
Sloughhouse	0.222	0.916	0.957	0.915	0.959	0.940	0.902	1.000							
Roseville	0.138	0.890	0.920	0.877	0.933	0.926	***0.935***	0.905	1.000						
Folsom-Natoma	0.183	0.906	0.941	0.892	0.952	0.940	0.928	***0.967***	***0.952***	1.000					
Auburn	-0.017	0.688	0.710	0.663	0.742	0.751	0.795	0.749	0.822	0.816	1.000				
Cool	0.040	0.783	0.792	0.752	0.815	0.821	0.842	0.823	0.886	0.890	***0.943***	1.000			
Placerville	-0.062	0.478	0.584	0.490	0.593	0.569	0.618	0.675	0.673	0.736	0.811	***0.836***	1.000		
Colfax	0.095	0.792	0.809	0.805	0.831	0.843	0.836	0.810	0.854	0.839	0.888	***0.895***	0.674	1.000	
Grass Valley	-0.157	0.066	0.122	0.020	0.160	0.155	0.257	0.224	0.228	0.279	***0.575***	0.436	0.434	0.434	1.000

than that of BBY. The maximum values captured at Elk Grove approach that of 70 ppb, the national safety standard, on a few days including August 12, and August 17, 2016 (Fig 19). This gives an indication of the marine influence, or higher humidity, on ozone concentrations at BBY, as well as the impacts of local emissions at inland sites. The correlations among all the fifteen surface ozone monitoring stations are in Table 2.

Correlations Among Sites

A correlation analysis was performed utilizing the calculated maximum daily 8-hour average surface ozone values. The calculated correlation coefficients for the 15 surface ozone monitoring stations are recorded in Table 2. The SAC sites are listed in order of lowest elevation to highest elevation above sea level. Correlations for the maximum daily 8-hour average ozone concentrations between two surface sites were calculated based on an exact date and hour comparison. The bold, italicized values within the table highlight the strongest correlation for each surface monitoring station. The strongest correlations between individual surface monitoring stations ozone concentrations were found to be within the sub-region height category: low, mid, or high. This gives indications of a regional ozone concentration affecting the total ozone concentration.

Low elevation surface monitoring site correlations for the calculated maximum daily 8-hour average ozone concentrations were reviewed. Each of the surface monitoring sites which were included in the low category are located below an elevation of 33 meters above sea level. Among the five low elevation surface sites, the strongest ozone concentration correlation was found between the T-street station and the Del Paso station. These sites are different in elevation by 15 meters, yet very similar in latitude (Fig 3). It was found that ozone concentrations at the Davis station had the strongest correlation with the T-street station (Table 2), located 4 meters difference in elevation above sea level. Also found was that the ozone concentrations at the North Highlands station had the strongest correlation with the Del Paso station, located just 3 meters difference in elevation. Still being a relatively strong correlation, the weakest correlation among the five sites was found between ozone observations at the Elk Grove station and the North Highlands station. Within the low category, these two monitoring sites are located lowest and highest in elevation above sea level. The Davis station and the Elk Grove station generally exhibited weaker correlations with the twelve other monitoring stations in SAC than the other three low category sites (Table 2). This would be expected as the Davis site is located furthest west and the Elk Grove site is located furthest south (Fig 3).

The correlations of the four mid elevation surface sites maximum daily 8-hour average ozone concentrations indicate that these sites are grouped semi-appropriately. Each of the four surface monitoring sites are located at an elevation between 47 meters and 108 meters above sea level. The strongest correlation found among the four mid sites was between the ozone concentrations at the Sloughhouse station and the Folsom-Natoma station, a correlation coefficient of 0.967 reported in Table 2. As expected, the weakest of the correlations was found between the ozone concentrations at the Sloughhouse station and the Lincoln station, a correlation coefficient of 0.902 is recorded. Of the four mid elevation surface monitoring sites, these two are separated by the greatest distance (Fig 3). It is interesting to note that the correlations among the mid and low sites are all strong correlations. This shows the importance of latitude and longitude among the ozone concentration correlations in the lower 110 meters of the SAC air basin.

Correlations among the high elevation surface sites are discussed. The Grass Valley station has its strongest correlation with the Auburn station, yet it is only a moderate correlation coefficient of 0.575 (Table 3). The correlations between the Grass Valley station and the rest of the surface monitoring stations was expected to be weaker than the others as it is located highest in elevation above sea level and furthest north. The Auburn station, the Placerville station and the Colfax station each displayed the strongest correlation with the Cool station. The Cool surface monitoring station is noticeably located at a central point between the three monitoring stations (Fig 3). Within the high category, the Cool station exhibited a correlation coefficient of 0.943 with the Auburn station. This is the strongest correlation within the category and the surface monitoring sites are closest in location.

Generally, as the distance between the two surface monitoring stations under comparison increases in the vertical and horizontal directions, the correlation becomes weaker. Therefore, it can be inferred that each of the three height categories have different regional ozone values contributing to the whole maximum daily 8-hour average ozone calculated value. Weak to little correlation are found between the BBY and the SAC maximum daily 8-hour average surface ozone.

The high elevation surface sites have both positive and negative correlations with the data captured by the BBY surface monitoring station (Table 2). The Colfax and The Cool monitoring stations both display very weak positive correlations with the BBY station. They also exhibited stronger correlations with the SAC monitoring sites than did the other three sites within the category. This stronger correlation could be due to the sites bearing of near 45 degrees from the heart of Sacramento. It is known that summertime thermally driven upslope flows will transport pollutants from Sacramento to the north-east Sierra Nevada foothills (Fast 2012). Therefore, these two sites would not be strong candidates to further understand surface pollution with influences from above. Three site locations, Auburn, Placerville and Grass Valley, each displayed a very weak negative correlation with the BBY surface ozone. These three high category sites each display weaker correlations with all the surface monitoring sites in comparison to the Cool and Colfax stations. The weak negative correlation values give an indication of a height dependency on the ozone correlation. For completion, a correlation analysis was performed for the five high elevation category surface monitoring stations against elevated BBY ozonesonde measurements.

The correlation analysis was performed as follows: between the observed 21z surface values at each of the high elevation surface monitoring locations with the BBY ozonesonde concentrations at levels between 400 meters and 1000 meters, and at 2000 meters. The results of the correlations are recorded in Table 3.

Using the elevated BBY ozonesonde data for comparison, the correlations with the high elevation surface ozone became generally stronger. At those locations which previously exhibited a negative correlation, the correlations became positive (Table 3). Of the five sites, the Placerville station exhibited the strongest correlations with elevated

Table 3. Correlation Coefficients for high elevation surface ozone values observed for the 21z hour with elevated Bodega Bay 21z ozonesonde measurements, bold italics are the three strongest correlations.

Correlation Coefficient	BBY 400m	BBY 500m	BBY 600m	BBY 700m	BBY 800m	BBY 900m	BBY 01km	BBY 02km
Auburn 21z	0.107	0.150	0.338	0.456	0.503	0.484	0.372	0.308
Cool 21z	0.173	0.165	0.326	0.406	0.478	0.451	0.319	0.414
Placerville 21z	0.358	0.482	***0.585***	***0.570***	***0.574***	0.515	0.545	0.272
Colfax 21z	-0.005	-0.002	0.120	0.130	0.137	0.088	0.110	0.326
Grass Valley 21z	0.236	0.211	0.276	0.203	0.203	0.129	0.159	0.174

BBY ozonesonde data. The exception to correlation improvement with height was unveiled by the observations at the Colfax station. The correlations between the Colfax surface ozone and BBY elevated ozonesonde data at 400 and 500 meters becomes negative, and essentially nonexistent. The correlations turned positive with an increase in height and remained weak. The strongest correlation being a mere weak 0.326 with BBY ozonesonde measurements at a height of 2 km. This again iterates the transport of surface pollution from the greater Sacramento area upslope to the NE Sierra Nevada foothills.

The correlation between Placerville surface ozone observations and BBY ozonesonde measurements varies depending on height. The Placerville surface ozone concentrations used were the 21z surface observations. This value represents the observation that is closest to the ozonesonde measurements which were released, obtaining measurements at 21z ± a quarter of an hour to observe the well-known daily maximum surface ozone concentration. The correlation has swapped from a negative weak correlation with BBY surface ozone, to a positive moderately strong correlation with BBY 600-meter ozone. Table 3 shows that the correlation with Placerville surface ozone became stronger as the data analyzed reached the same elevation, then the correlations generally weakened again with ascending height. This is the type of relationship expected for locations that are a distance apart yet can be defined as similar regions under certain circumstances. The Placerville observations were then picked for further analysis.

Figure 20 is a linear regression plot for the comparison of BBY 600-meter ozonesonde measurements and observed surface ozone measurements in Placerville for the afternoon hour of 21z. The correlation coefficient (r) indicates the strength of the relationship between the two locations and the r^2 value is an indication of how dependent/independent the values at one location are on the other. The 600-meter BBY ozonesonde data and the 21z Placerville surface ozone exhibited a moderately strong correlation of 0.585. These sites also exhibited a dependent/independent factor of 0.342 for the case study period. This relationship is shown in Figure 20. It can be inferred that the ozone at either two locations were not generally influenced by the same source. Yet there were instances where the ozone entering these locations were influenced by the same source region. Recognizing that ozone observations at both locations exhibited similar daily variation in observed ozone four dates of interest emerged (Figs 20, 21).

A comparison of surface data at Placerville and elevated BBY ozonesonde data shows the similarities between the two locations. The two locations are roughly 200 km apart in a straight line. From the comparison of the two locations during the case study period, there were four dates of interest. On these dates, both locations experience similar daily changes in ozone (Fig 21). The dates were as follows: July 27, August 4, August 12, and

August 14. During these four instances at both locations, changes in the observed/measured ozone varied by the same concentration (±1.) from the day prior. During these four instances, both sites variance was seen to match in its directional change of either an increase or a decrease. This indicates that both locations became regionally similar, more than likely due to the influence of stratospheric ozone exiting or entering the larger region. The details for each date are further discussed in order of occurrence. On July 27, 2016 the afternoon ozone concentration observed at both locations were lower than the day prior. Both the BBY 600-meter ozonesonde measurement and the Placerville 21z

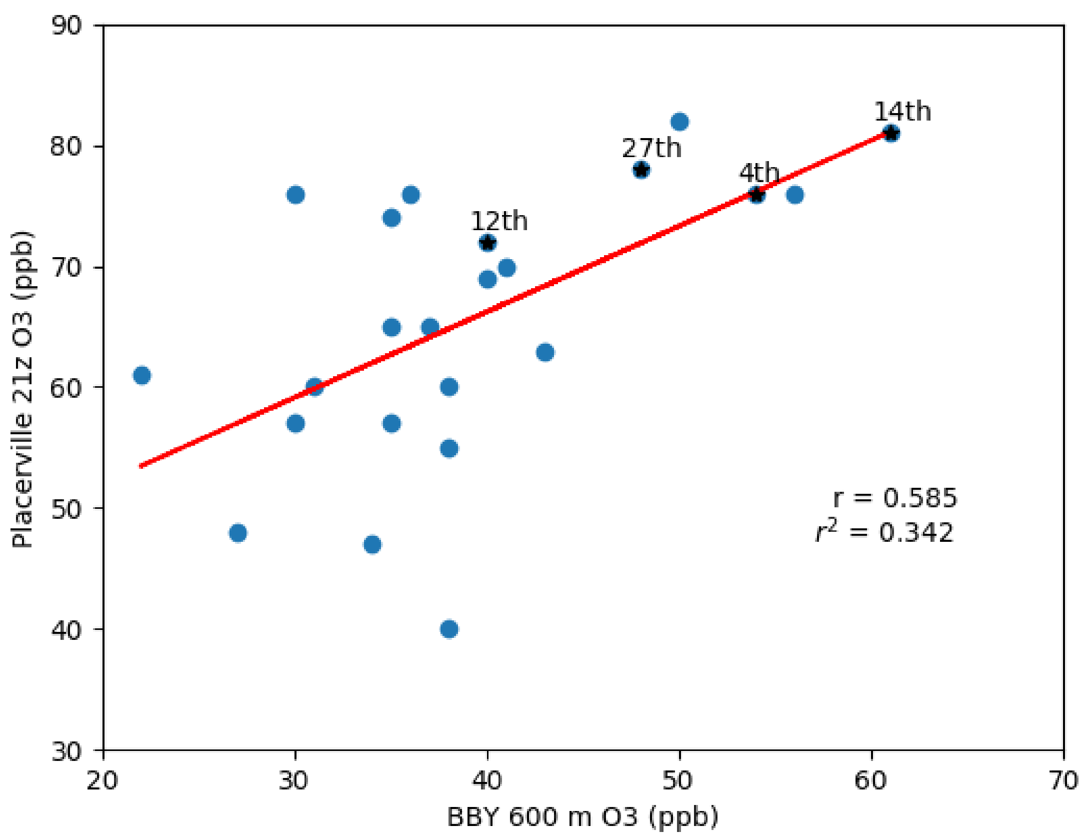

Figure 20. Linear Best-fit plot for 600-meter BBY observed ozone and Placerville 21z observed surface station ozone for the case study period July 25 – August 16, 2016; blue dots – observations.

surface ozone observation decreased by 13 ppb (Fig 21). The BBY 600-meter observation decreases from a concentration of 61 ppb to that of 48 ppb on July 27. This is a 27% decrease in ozone at BBY 600-meter from the day prior on July 26. The Placerville observed surface ozone measurement at the 21z afternoon hour was 91 ppb and decreased to 78 ppb on July 27. This is an observed decrease in surface ozone concentration of 17% at the Placerville surface monitoring station.

Of the four instances, August 4, 2016 is associated with the greatest daily change in observed ozone. This is the only instance of the four where the daily change in observed ozone concentration at Placerville and BBY 600-meter differ by 1 ppb. On August 4, the observed BBY 600-meter ozonesonde measurement was 54 ppb (Fig21). A reduction of 27 ppb from the day prior on which an observation of 81 ppb was measured. From August 3 to August 4 this was an observed change in ozone of 100% at BBY 600-meter.

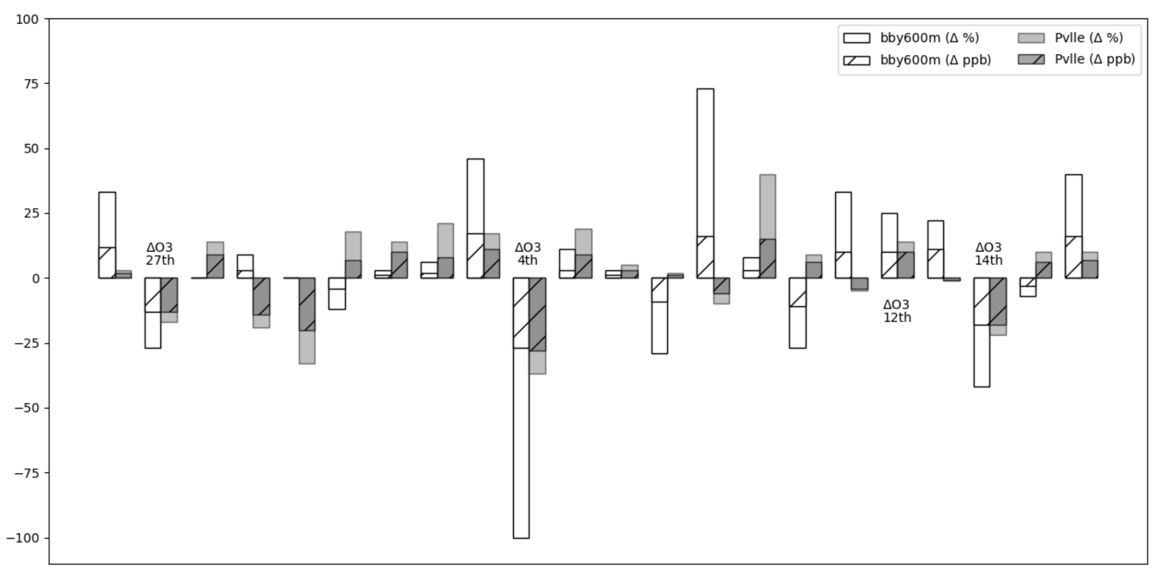

Figure 21. Daily observed ozone variations, in both changes in percentage (solid bar) and in concentration (hatched bar), for 2 locations: BBY 600-meter (white) ozonesonde observation and 21z Placerville (light gray) surface ozone observations at 612 meters. Case study period July 25 – August 16, 2016.

In Placerville at that time, the observed surface ozone concentration decreased by 28 ppb to the 21z observed concentration on August 4 of 76 ppb. The day prior, the Placerville surface ozone concentration at 21z was observed at 104 ppb. This is a decrease in the observed daily ozone by 37 % at the Placerville surface ozone monitoring station.

The third instance occurred on August 12, 2016 and is the only one of the four instances which both locations observed ozone concentrations simultaneously increase. At both locations an increase of 10 ppb is observed in the daily change of ozone (Fig 21). For BBY 600-meters, the concentrations changed from 30 ppb on August 11 to an observed value of 40 ppb on August 12. For this day at BBY 600-meter this gives a 25% increase in observed ozonesonde measurements from August 11 to August 12. In Placerville, the observed surface ozone measurements increased from 62 ppb on August 11 to a concentration of 72 ppb on August 12. This is a 14% increase in daily ozone observations from August 11 to August 12, 2016.

The final instance of similar daily ozone variations for the selected case study period occurred on August 14, 2016. Notice in Figure 20 that on this date at both locations the greatest ozone concentrations of the case study period were observed. This common decrease among the two locations could be in association with the common increase in ozone concentration just two days prior. On August 14, the observed concentration of the BBY 600-meter ozonesonde was 61 ppb. This value is 18 ppb less than the day prior when a concentration of 79 ppb was observed at BBY 600-meter. This is an observed decrease in ozone of 42% for BBY 600-meter observations (Fig 21). The decrease in concentration observed from August 11 to August 12 at the Placerville surface monitoring station was also 18 ppb. The observed daily decrease was from a concentration of 99 ppb to that of 81 ppb on August 12, 2016. This is an observed reduction in surface ozone of 22% in Placerville.

Though the observed daily changes in ozone concentration can be the same among both locations, the effect on the overall ozone concentration total is much more influential at the North Bay Area coastal site than the Sierra Nevada Foothill surface site. This is visible in the daily ozone percent changes calculated for the observed BBY ozonesonde measurements (Fig 21). During this case study period, the daily percent changes were greater than the daily percent changes calculated for the ozone observation in Placerville. The simultaneous daily ozone changes of the same concentration observed at both locations are proof of these two locations being under the same regional influence. The increase to the 600-meter region on August 12, followed by the decrease on August 14, align with the downward progression of increasing ozone that began near the tropopause on August 5, 2016 with the second intrusion of interest (Fig 15).

Conclusion

Surface ozone concentrations are closely monitored across the globe. Regulations of this pollutant are set nationally by the EPA to monitor the safety of human health and ecosystems. The maximum observed ozone at surface sites typically occurs in the afternoon when the convective boundary layer is fully developed, allowing for the strongest regional effects on surface ozone. An increase of surface ozone above the set pollution standard due to stratospheric influence would be excluded in regulatory determinations.

Stratospheric intrusions are known to be plentiful above the California region, especially along the North Pacific storm tracks. The use of PV as a tracer for the dynamical tropopause and the study of stratospheric-tropospheric exchange has occurred for decades. Recall that the accepted value among the community ranges from 1 – 5 PVU, with the lower values capturing the deeper penetration of stratospheric air into the lower tropopause. Deep stratospheric intrusions were found to be plentiful above Northern California during late July and early August. This study shows the importance of using 1.5 PVU to identify the dynamical tropopause above Northern California. Also, observations during this study period demonstrate that the value of 1.0 PVU is optimal to observe the deep penetration of stratospheric air masses into the lower troposphere.

It is widely accepted that the observed values of ozone measured at western coastal sites are a good indication of background ozone values due to the prevailing onshore flow. Therefore, the ozone concentrations measured at BBY show the variability of background ozone due to stratospheric influence without strong anthropogenic influences. Under certain meteorological conditions the background ozone, the concentrations that are without local influences, measured aloft at BBY may be transported further inland and mixed down to the surface. Yet the ozonesonde measurements are representative of large horizontal regions. Therefore, during a stratospheric intrusion over the larger region, direct transport of ozone from the coastal area is not required to explain the observed correlations in ozone (Liu et al. 2009).

The vertical air columns above BBY and SAC are shown to be analogous during the occurrence of stratospheric intrusion events over Northern California. This study recognizes the similarities detected within the average values of PV, ozone, RH, and SH for the defined BBY and the SAC regions. Therefore, it could be concluded that the ozone measurements captured by the BBY ozonesonde give a good indication of ozone concentrations elevated high above the SAC region. The strongest spatial similarities exhibited were in the vertical column of air above 2 km mean sea level.

This study clearly shows the downward vertical transport of ozone from the point of stratospheric injection to the surface at BBY. In regions of stratospheric ozone intrusion events, noted by high PV, a downward progression of increasing ozone with time is distinct within the BBY ozonesonde daily percent change data. The positive increase in ozone was tracked downward, reaching the lowest 1 km of the ozonesonde profile and the surface within a week. These same ozone increases were noticeable in the observed ozone maximum daily 8-hour average values from the BBY ozone monitoring station.

This study clearly shows that the highest elevation ozone monitoring sites experienced mean values near the EPA national standard of 70 ppb during the case study period. During this selected timeframe, the air quality proved to be moderate to harmful in the southern Sacramento Valley. This study shows that the high category elevation surface sites often contribute to this non-attainment. Also, the reduced daily range of maximum daily 8-hour average surface ozone at the high elevation sites gives an indication of a greater influence of background ozone than local ozone in comparison to the lower elevation surface monitoring sites.

The strongest correlations among the SAC surface monitoring sites were within the height/region category. Though observed ozone concentrations were very similar when sites are in close proximity, the small difference shows that ozone is highly variable. This implies that correlations between observations of ozone concentrations at similar altitude over a greater distance would not be expected to be very strong. A moderate correlation would indicate that air masses observed at two sites become regionally similar during events that cover a greater region simultaneously, such as during stratospheric intrusions.

Weak to little correlation was found between the BBY and the individual SAC maximum daily 8-hour average ozone concentrations observed at the surface. This would be expected as the locations are generally not categorized within the same region. The regions are separated topographically and are known to each be influenced by different boundary layers.

Elevated surface monitoring sites in the lower foothills of the Sacramento Valley can be separated into two categories. One category includes sites which ozone observations are influenced by lower elevation surface pollution. The Colfax monitoring site has a strong correlation with most of the SAC surface monitoring sites. The negative weak correlation found between the Colfax surface ozone and the elevated heights of the BBY ozonesonde data further contributes to knowledge of surface pollution from the heart of Sacramento being transported North Easterly upslope to the Sierra Nevada Foothills. A second category includes sites which are influenced by the ozone in an upper level air mass. A height dependency correlation between BBY and high surface elevation sites in SAC shows a change from a weak negative correlation to a moderate positive correlation for three ozone monitoring sites; Grass Valley, Placerville and Auburn. This shows that ozone concentrations observed at these surface sites were more closely related to the air above than to the air below.

This study demonstrates that surface ozone in Placerville and the air mass elevated above BBY were influenced similarly by stratospheric ozone during a stratospheric intrusion event to the region of Northern California. A moderately strong correlation was found between the observed afternoon Placerville surface ozone concentrations and the BBY 600-meter ozonesonde measurement. It was observed that daily changes in ozone, as either a decrease or an increase of the same concentration, do occur between the 21z ozone observation at the Placerville surface station and the BBY 600-meter ozonesonde measurements. The occurrence of this is suggestive of both locations simultaneously being influenced highly by background ozone that is stratospheric in nature and can be considered a regional influence. Therefore, a closer study of the vertical column of ozone above both the BBY and SAC regions during forecasted stratospheric intrusions via simultaneous ozonesonde launches could lead to quantifying the direct influence of stratospheric ozone contributing to the total surface ozone pollution in the southern Sacramento Valley.

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